Highly Directive Package-Integrated Dipole Arrays for Low-Cost 60-GHz Front End Modules

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***Abstract*—Package-integrated highly directive dipole antenna and dipole array with an original feeding technique are presented. The proposed design features excitation of low-cost organic-based substrate elevated directive dipoles with vias. A miniature substrate embedded feed network is provided for direct via interconnection between the antenna and a chip embedded in the same stack-up. The simulated single dipole (10 × 10 × 0.635 mm^3) exhibits more than 11 GHz bandwidth (56 to 67+ GHz), 7.83 dBi peak directivity, and 91.7% efficiency. A prototype of an 8-element dipole array (22 × 11 × 0.635 mm^3) is measured and exhibits 8 GHz bandwidth (56.6 to 64.6 GHz), 15.1 dBi peak gain at 61 GHz, and 75 to 83% estimated efficiency.**

***Index Terms*—60-GHz, directive antennas, dipole antenna, dipole arrays, packaging.**

I. Introduction

Next generation high-data-rate wireless products are being developed by consumer electronics industry using 60-GHz radios for short-range communication applications, including Wireless Personal Area Network (WPAN). The applications in this FCC allocated unlicensed, wideband frequency (57–64 GHz) spectrum require highly secure, interference-free operation with high-density, multiple-radio deployments. Narrow beamwidth antennas increase security as well as enable communication with minimal interference in a highly dense wireless environment. To efficiently focus the radiated energy toward a desired end point, highly directive antennas are essential at the radio front-ends. Moreover, in the current cost-competitive wireless market, the antennas should utilize low-cost package and fabrication technology and be off-chip to reduce the IC as well as overall module cost. These challenges motivate the designers to look beyond just the electrical performance of antennas to a system-level modular integration approach.

To date, three effective packaging approaches have been proposed for 60-GHz antenna design. Air-suspended superstrate antennas that can be flip-chip bonded to the IC have been demonstrated with better than 13% impedance bandwidth and about 8 dBi gain [1]. The fragility of the fused silica antenna substrate requires manual assembly steps that increase the cost. The end product also needs to be encapsulated for protection purposes. The second approach uses low temperature co-fired ceramic (LTCC) multilayer technology to design an antenna in package (AiP) solution that is wire bonded to the 60-GHz chip [2]. The actual AiP wire bonded to a chip was not measured, but it is expected to have slightly less than 10% frequency bandwidth and 7 dBi gain after compensation for the wire-bonding parasitics. This solution results in low fabrication cost, but the bond wires increase its complexity. Another antenna packaging approach, that delivers increased integration levels, uses high-resistivity silicon to flip-chip bond a cavity backed antenna with the 60-GHz chip [3]. Antennas with greater than 10% frequency bandwidth and 6 to 8 dBi gain have been demonstrated. This approach uses existing semiconductor processing, but involves complex and costly steps, such as deep reactive ion etching of the cavity and critical alignment of the antenna to the cavity.

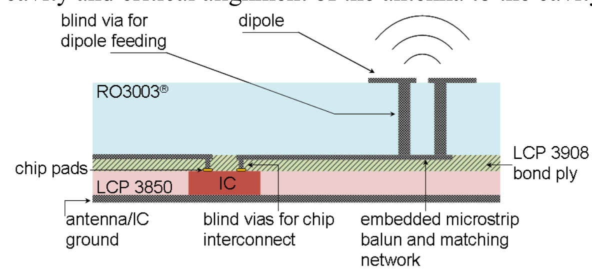

Fig. 1. Conceptual drawing for the proposed dipole antenna integrated with an embedded 60-GHz chip.

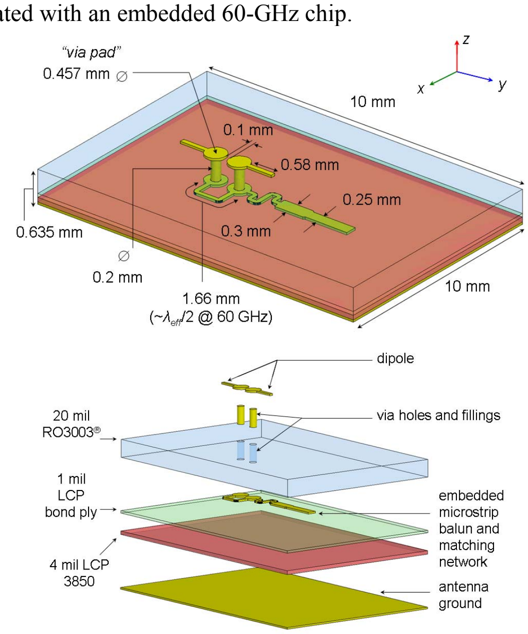

Fig. 2. Detailed view of the proposed package-integrated dipole.

In this paper, a low-cost 60-GHz AiP solution based on lamination of multiple dielectric layers with via interconnects is proposed. The proposed design is an enhanced directivity dipole antenna via fed with a substrate embedded balun and matching network densely packaged in a multilayer assembly. The antenna can be built and laminated in an organic stack-up containing embedded chips, as shown in Fig. 1. The feasibility for laminating substrate embedded active circuits with other circuitry has been demonstrated in [4]. Figure 2 shows a detailed view of the proposed antenna. The feeding technique using micro-vias from low-cost organic material stack-up reduces interconnection parasitics for embedded chips at 60-GHz.

In Section II, the design and practical implementation of the proposed highly directive dipoles are discussed. Design and measurements on a high gain 8-element array is presented in Section III. Measured results show that this array is the highest gain for this size antenna reported so far on low-cost organic technology, to the best of our knowledge.

II. Package-Integrated Dipole Antenna Design

It is well known that a half-wavelength dipole antenna, in free space, has a low directivity (2.15 dBi). Image theory stipulates that, for an electric dipole horizontally elevated above a highly conductive ground plane, the directivity can be substantially increased [5]. The source dipole and its image have equal amplitude but they are out-of-phase. They also form an array that is known to have a beam that peaks in the direction perpendicular to the ground plane when the source dipole is less than or equal to a quarter-wavelength above the ground plane. Our goal is to have an antenna that radiates at boresight. Full wave simulations on the multilayer integrated antenna structure using Ansoft HFSS [6] are performed. The simulated boresight directivity of a half-wavelength dipole at a height h above a finite ground plane (10×10 mm^2) is shown in Fig. 3. It is seen that the directivity peaks at 7.67 dBi when h=0.7 mm (~$0.25\lambda_{eff}$). λ_{eff} is the effective wavelength inside a dielectric medium of relative permittivity 3, at 60 GHz. The radiation efficiency is higher than 99 % above 0.5 mm.

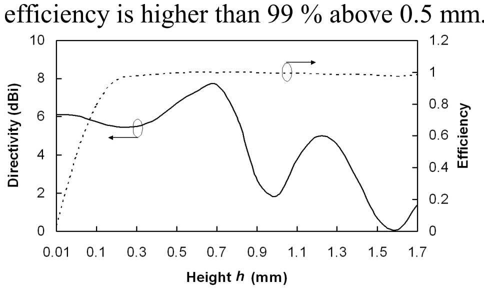

Fig. 3. Variation of directivity and efficiency of the horizontal dipole at a height h above a finite ground plane.

After establishing the optimal dipole height, a feeding network is designed to keep the overall antenna structure compact without altering its radiation performance. For printed dipole antennas, the feeding transmission line may be directly printed on the same layer as the dipole. However, transmission lines such as microstrips printed on a thick substrate tend to be excessively wide, and are particularly undesirable in antenna array configurations. Alternatively, the feed line can be printed on a sub-layer (hence substrate embedded), closer to the ground plane, to reduce the feed line width and the feeding network form-factor. Taking advantage of multilayer capabilities of Rogers RO3003® and LCP materials, this solution can be easily implemented. These materials have a relative dielectric constant close to 3 and excellent loss performance at 60-GHz ($\tan\delta_{LCP}$ = 0.004, $\tan\delta_{RO3003}$ = 0.002).

A miniature substrate embedded feed network composed of two vias, a balun and a matching network for 50 Ω input impedance is designed to drive the dipole. To closely match the simulated optimal dipole height of 0.7 mm, we use the substrate stack-up shown in Fig. 2. The dipole is printed on top of a 20 mil thick RO3003® substrate that is traversed with two blind vias that connect to the balanced input of a microstrip balun printed on the opposite side of this substrate. The balun is integrated with a microstrip matching network. The ground for the microstrip is provided on the bottom side of a 4 mil thick LCP layer. Finally, the two above mentioned layers are bonded together using a 1 mil thick LCP bond ply. The dimensions of the antenna structure are shown in Fig. 2.

The 180° microstrip balun feeds the two dipole arms out-of-phase with almost the same amplitude. The phase shift is achieved with a 0.1 mm wide and 1.66 mm long microstrip line. The amplitude attenuation through the phase shifter is less than 0.1 dB, which guarantees an equal amplitude feeding of the dipole arms. At the unbalanced input of the balun, a 0.1 mm wide and 1 mm long meandered microstrip line acts as a series inductor to center the resonant frequency of the dipole around 60-GHz; the simulated input impedance is $(38.5 + 1 \cdot j)$ Ω. The antenna is then matched to 50 Ω with a quarter-wavelength transformer.

The proposed dipole is matched from 56 GHz to >67 GHz covering the entire WPAN band (Fig. 4a). The radiation pattern shown in figure 4b is perfectly symmetric in both E (yOz) and H (xOz) planes, with a peak of 7.83 dBi at boresight, and the antenna radiation efficiency is 91.7 %. The structure of the proposed embedded feed network along with the 180° balun is critical in the achievement of the E/H plane pattern symmetry. The peak directivity is very close to the ideally fed dipole of Fig. 3 whereas the efficiency drops by only 0.08 %, which is attributed to the insertion loss through the vias and the feed network.

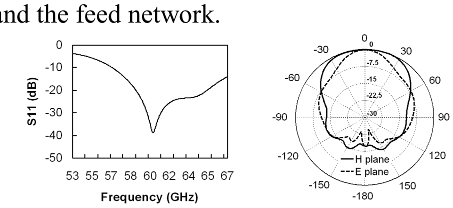

Fig. 4. Simulated (a) S_{11} and (b) directivity of the proposed package-integrated dipole antenna.

III. Package-Integrated 8-Element Dipole Array

A. Dipole Array Design

The proposed single dipole antenna has a significantly high enough gain (7.68 dBi) for 60-GHz high speed communications at moderate distance ranges. However, for applications at a distance of several meters, the antenna directivity needs to be enhanced, and this can be achieved with dipole arrays. In order to increase the antenna directivity, a compact (22 × 11 × 0.635 mm^3) 8-element linear array based on the single element dipole presented in Section II is designed. A corporate feed network is used in this antenna array. The dipoles are spaced half a wavelength from each other in the x−direction. EM simulations indicated that this spacing provides at least 18 dB isolation between adjacent elements.

Fig. 5 shows a schematic of the designed array with a photograph of the fabricated part. Since this antenna structure has an embedded microstrip feed line, it requires a transition to an external feed for antenna testing. A low-loss broadband microstrip-to-CPW transition is developed in the frequency band of interest, based on the approach of reference [7]. The operation of this transition is based on magnetic coupling between the overlaying microstrip line and the orthogonal slot line, which is then appropriately bent to form a CPW line. The CPW dimensions were fixed to 1300 µm/100 µm because of the limitations in the lithography process used by the PCB circuit manufacturer. The center conductor width of the CPW line is further tapered down to 400 µm for a good transition to the GPPO connector.

Manufacturing of this antenna structure is achieved using standard printed circuit board processes for high volume and low-cost production. From an integration perspective, the proposed embedded active die approach is also attractive for 60-GHz applications. In this cavity embedded die approach, polymer materials are typically ablated with UV excimer laser within microns accuracy to create the cavities. A reasonable gap width of 10-25 µm is thus achievable between the edges of the cavity and the die, keeping the die well aligned inside the cavity. Due to the minimal difference in the thermal coefficient of expansion between LCP and RO3003® materials, mechanical stress at the chip ports is minimized; hence reducing chances of interconnects failure. Furthermore, using this approach, the antennas and chips do not need to be encapsulated in a mold material, which significantly decreases assembly complexity and preserves the antenna performance.

To measure the radiation pattern of the array, the embedded 50 Ω microstrip line has been extended to 25 mm; this helps isolating the antenna and the bulky GPPO connector. Because of the long microstrip line (0.5 dB/cm), the vertical transition (0.3 dB) and the GPPO to 1.85 mm adapter (0.9 dB) used in measurements, about 2.45 dB of loss is expected from the reference plane P to the input of the 1.85 mm adapter.

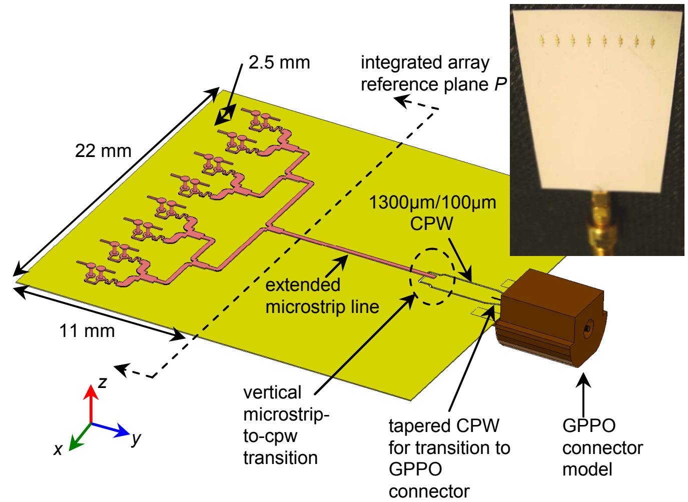

Fig. 5. Schematic and photograph of the measured 8-element package-integrated dipole array.

B. Dipole Array S_{11} Evaluation

The reflection coefficient of the array is simulated and measured at the input of the connector. The fabricated array is plugged to a GPPO to 1.85 mm adapter, which is connected to a calibrated Agilent network analyzer. Simulation at plane P where the antenna is to be actually connected to a chip in an integrated system is also performed.

At reference plane P, the 8-element array exhibits more than 11 GHz bandwidth (56 to above 67 GHz - S_{11}<-10 dB). After inclusion of the extended microstrip line and GPPO connector, the simulated array is matched from 54 GHz to above 67 GHz, whereas the measured array has 8 GHz bandwidth (56.6 to 64.6 GHz - S_{11}<-10 dB). The narrower measured bandwidth is attributed to mismatching through the different transitions, especially the transition to the GPPO connector that has a response sensitive to the accuracy of mounting the connector on the test board. During mounting of the GPPO connector on the test board, there is always a 50 to 100 µm gap between the actual CPW input and the connector (Fig. 6b). This gap introduced parasitic capacitance that degraded the S_{11}. The multiple reflections that appear in the blue and red curves are effects of the transition to the GPPO connector.

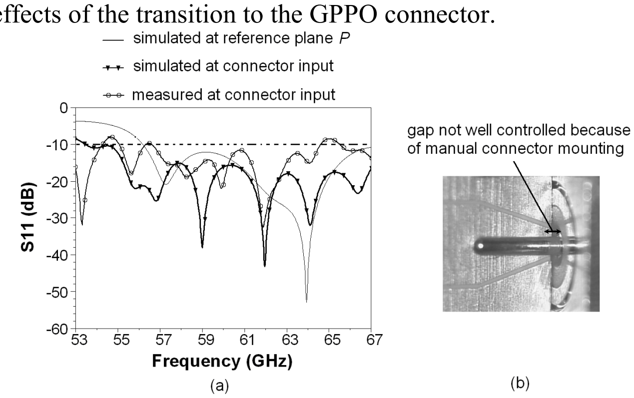

Fig. 6. (a) Simulated and measured 8-element array S_{11}; (b) photograph of the CPW to GPPO transition.

C. Dipole Array Radiation Performance

The dipole array is characterized in a 60-GHz antenna system that holds the antenna under test (AUT) in a fixed location, where it acts as the transmitting antenna. A receiving V-Band horn antenna rotates in an arc with a radius of 52 cm around the AUT. The AUT and horn are connected to a VNA with a low noise amplifier on the receiving port.

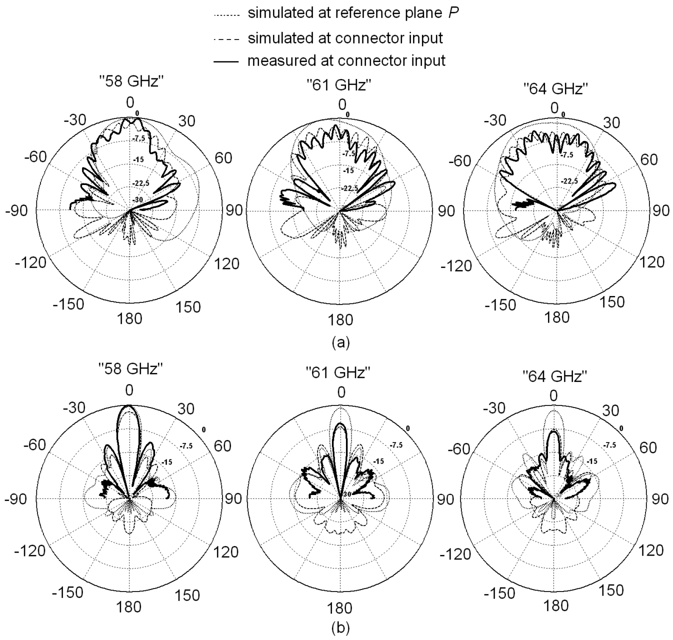

Fig. 7. Simulated and measured normalized (a) E plane; (b) H plane radiation patterns.

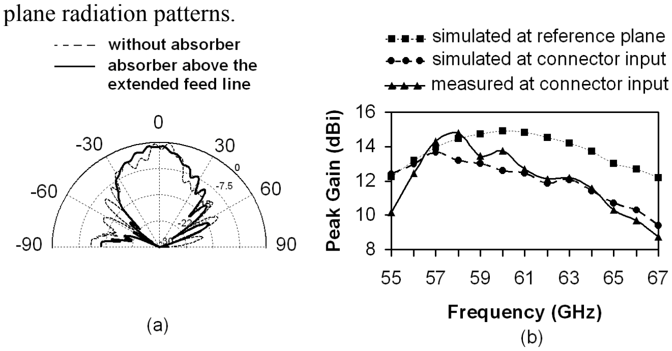

Fig. 8. (a) Measured normalized E plane pattern at 58 GHz: extended feed line effects; (b) simulated and measured peak gain.

The normalized radiation patterns of the antenna array are plotted at 58 GHz, 61 GHz and 64 GHz. The E and H plane simulated (with GPPO connector) and measured patterns are all in good agreement. In the E-plane, several ripples with 1 to 3dB amplitudes are observed, in both simulation and measurement with the extended feed line and the GPPO connector. By carefully covering the long feed line with a 3 mm thick mm-wave absorber, those ripples are smoothed out to less than 1 dB amplitude, as seen in Fig. 8a. The field radiated from the extended embedded microstrip line is found to be the main cause of those ripples in the E plane patterns. Since the long feed line is perpendicular to the H plane, it does not introduce any perturbation in the H plane patterns. In the E-plane, we observe a minor beam skewing over the frequency band that is attributed to amplitude and phase imbalance of the balun.

Fig. 8b shows the peak gain level variation over the frequency band. As expected the simulated and measured peak gain levels at the GPPO input are about 2 dB less than the simulated levels at reference plane *P*, above 60 GHz. From 55 GHz to 60 GHz, there are a few points that do not follow the same trend as the simulated peak gain at plane *P*. Those discrepancies are attributed to the ripples from the adjacent embedded parasitics that create irregular peak gain levels.

After de-embedding the 2.45 dB loss in the feeding network, the 8-element dipole antenna array exhibits a peak gain of 17.23 dBi at 58 GHz, 15.1 dBi at 61 GHz, and 14.02 dBi at 64 GHz. The estimated radiation efficiency is 68 to 70 % at the GPPO input and 75 to 83% at reference plane *P*.

VII. Conclusion

Highly directive dipoles and arrays for integration with compact low-cost 60-GHz antenna-integrated radio front end modules have been developed on multi-layer organic substrate stack-up with state of the art performance. A new excitation scheme using vias and a substrate embedded feeding for direct interconnection with embedded active ICs has been proposed. A single dipole ($10 \times 10 \times 0.635$ mm^3) has been designed with more than 11 GHz bandwidth, 7.83 dBi peak directivity, and 91.7% efficiency. An 8-element dipole array ($22 \times 11 \times 0.635$ mm^3) has been measured with 8 GHz bandwidth, 15.1 dBi peak gain at 61 GHz, and 75 to 83% estimated efficiency. The simplicity of this novel approach and the unique performance of the proposed structures meet the requirements for compact low-cost multi-layer package-integrated 60-GHz antennas.

Acknowledgment

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