A Multilayer Organic Package with 64 Dual-Polarized Antennas for 28GHz 5G Communication

Xiaoxiong Gu1, Duixian Liu1, Christian Baks1, Ola Tageman2, Bodhisatwa Sadhu1, Joakim Hallin2, Leonard Rexberg3, and Alberto Valdes-Garcia1

1IBM Research, New York, USA, 2Ericsson, Lindholmen, Sweden, 3Ericsson, Kista, Sweden

Abstract—An organic-based multi-layered phased-array antenna package for a 28GHz 5G radio access application is hereby introduced. The package incorporates 64 dual-polarized antenna elements and features an air cavity common to all antennas. Direct antenna probing measurements of the package show over 3GHz bandwidth and 3dBi gain at 28GHz. A phased array transceiver module has been developed with the package and four SiGe BiCMOS ICs are attached using flip-chip assembly. Module-level measurements in TX mode show 54dBm EIRP and near-ideal 35dB gain increase for 64-element power combining. 64-element radiation pattern measurements are reported with a steering range of > ±40 degrees without tapering in off-boresight direction.

Index Terms—5G mobile communication, antenna-in-package, phased array.

I. INTRODUCTION

Silicon-based millimeter-wave (mmWave) phased-array antenna solutions, with their electronic beam-forming and beam-steering capabilities, compact form factor, and affordability, are particularly suitable for fifth generation (5G) mobile access systems [1–3]. Recent Si-based phased arrays with antennas in package have been demonstrated for the 60GHz and 94GHz bands using various substrate technologies, including those built with liquid crystal polymer (LCP) based board processes [4], organic buildup substrates [5], glass substrates [6], low-temperature co-fired ceramic (LTCC) substrates [7], silicon interposers [8] and molding-compound based wafer-level substrates [9]. Phased array scaling approaches with antennas in silicon have also been demonstrated including TSV-last chip integration with glass [10] and wafer-level sub-reticle stitching [11]. However, many challenges for packaging such solutions remain, including integration support for dual-polarized antenna array operation at 28GHz, realizing the desired high radiation output power while maintaining the per-element bandwidth and radiation patterns required for beam forming and steering, and supporting the required increased package form factor with its associated increases in thermomechanical and cooling solution complexity.

The multi-chip antenna-in-package module reported here addresses these challenges. It supports four 28GHz flip-chip mounted transceiver ICs supporting dual-polarized operation in TX and RX modes [3], incorporates 64 embedded antenna elements, and enables a reliable board-level assembly via a ball-grid-array (BGA) interface with direct heat sink attachment for effective thermal management. The organization of the paper is as follows: Section II describes an overview of the antenna-in-package design and implementation. Section III presents antenna characterization results, including direct passive probe measurements of individual elements and active module measurements of 64-element beam formation. For design optimization and verification, full-wave electromagnetic simulations of the entire antenna array package have been performed and model-to-hardware correlations of radiation patterns are demonstrated in the paper.

II. ANTENNA-IN-PACKAGE OVERVIEW

Fig. 1 illustrates the antenna-in-package layer stackup, assembly breakout and the mounting concept with IC and printed circuit board (PCB). The assembled package consists of a 2-layer lid substrate, a 2-layer frame, and a 14-layer base substrate. A dual-polarized aperture-coupled patch structure with air cavity is implemented for the antenna array. Both H- and V-polarization signals are input on the bottom C4 pads from ICs, fan out on the M6 layer, and feed radiator structures located on the M12 and M14 layers, respectively. The stacked patches are implemented using L1 and L2 layers in the lid substrate. A uniform air cavity is formed between the lid and base substrates in the package to increase antenna bandwidth and gain, and, at the same time, reduce the impact of surface waves on coupling between antenna elements.

Fig. 1. An illustration of antenna-in-package assembly breakout (top), layer stackup and board-level mounting concept (bottom).
Fig. 2. Top view (left) and bottom view (right) of a fully assembled antenna array package with mounted BGA solder balls and four transceiver ICs.

The RFICs are flip-chip attached to the bottom side of the package before being under-filled for C4 protection. The package is further mounted to a second-level PCB via BGA balls at the bottom. To enable cooling of the RFICs, there are cut-outs in the PCB in the region underneath each die that allow fitting of a heat sink with pedestals. Thermal interface material (TIM) is applied at the junctions between ICs and the heat sink.

Fig. 2 illustrates top and bottom views of the antenna array package. The package dimensions are 70mm × 70mm × 2.7mm. The RFIC size is 10.6mm × 15.6mm. There are in total 100 (10 × 10 with a 5.9mm pitch) antenna elements on the package: 64 active elements fed by four ICs and 36 dummy elements. The dummy elements are placed around the periphery of the package to maintain uniformity of the radiation patterns of the active elements. On the bottom of the package base, 655 BGA balls at a 1.27mm pitch provide the ICs with four power supplies, ground connections, digital controls, IF, and LO signals.

III. CHARACTERIZATION AND TESTING RESULTS

A. Passive Individual Antenna Element Characterization

Direct probe measurements of single antenna elements at the front-end signal C4 pads of a bare package were performed in an antenna chamber. Return losses for both H- and V-polarization are plotted in Fig. 3. The measured bandwidths of the antennas at -10dB are 3.7GHz for H-polarization and 3.3GHz for V-polarization, respectively, which is typical for all the elements. Measured radiation patterns in the E-plane for H-polarization and in the H-plane for V-polarization are also shown in Fig. 3. In the boresight direction, the measured antenna gains are 3dBi and 4dBi for H- and V-polarizations, respectively. The measured element patterns maintain a broad shape suitable for wide range beam-steering, showing gains of more than 0dBi over a 50 degree range in the H-plane and over a 40 degree range in the E-plane off-boresight direction. Furthermore, the measured element patterns demonstrate model-to-hardware correlation with the simulation results obtained from a full-wave EM model of the entire package.

Fig. 3. Antenna testing chamber and setup for passive antenna element probing measurement (top-left); measured frequency matching of a single element for H- and V-polarization (top-right); model-to-hardware correlation of radiation patterns: H-plane for V-polarization (bottom-left) and E-plane for H-polarization (bottom-right).

B. Active Module Characterization of 64-element Beams

Fully assembled antenna array modules with ICs and BGA balls were screened using a test board with a custom-made socket. Digital control functionalities and dual-polarized radiation performance were verified for all elements prior to soldering the module to the PCB. External IF and LO signals were connected to the 4 ICs via on-board splitters and baluns as shown in Fig. 4.

A functional module was characterized in the antenna chamber with a 1.84m distance between the module and a receiving horn antenna (Fig. 4). An FPGA board and a fan were connected to the test board for digital programming and air-cooling. Two motors were mounted to the fixture to provide rotation capability in both azimuth and elevation angles to support radiation pattern measurement.

Fig. 5 plots the measured radiation output power in H-polarization when 64 elements are phase aligned sequentially for power combining. The achieved 35dB increase that is demonstrated for 64-element combining as compared to single element output is consistent with the 36dB theoretical limit. A total maximum saturated EIRP of 54dBm was achieved in the measurement.

Next, 64-element radiation patterns were measured in TX mode. Fig. 6 plots the normalized boresight H-polarization patterns in the E- and H-planes, respectively. Here, an identical PA bias setting is applied to all the front-end elements. Without element amplitude calibration or tapering 12-degree half-power beam width, lower than -12dB side levels and over 20dB deep notches between the main and side lobes are...
observed which is expected as an intrinsic property of antenna arrays without antenna tapering. Realistic amplitude tapering may improve the side lobe level to around -20 dB which is close to practically achievable limits. Fig. 7 plots two measured 64-element H-polarization patterns steered to ±40 degrees off-boresight in the E- and H-planes, respectively, with lower than -10dB side lobe levels. The measured patterns agree with the full package EM simulation, validating the overall antenna-IC-package co-design and implementation.

IV. CONCLUSION

A 28GHz phased-array antenna-in-package module with 64 dual-polarized elements has been implemented and characterized. Measurement results on an assembled phased array module including the package and four transceiver ICs show over 50dBm EIRP in TX mode and ±40 degrees scanning range.

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