A High-Density Organic Package Solution to W-band SiGe Flip-Chip Applications

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***Abstract*—High-density packaging concepts need to be studied to meet the demands from telecommunication and radar applications which require large operational bandwidth and system compactness. In this work, package design of a transmitter SiGe flip-chip with C4 solder ball interface on a multilayer PCB operating around 94 GHz is presented.**

Keywords*—*W-band, multi-layer organic package, flip-chip, SiGe

I. Introduction

With the increase in demands from wireless communication in both civil and military applications, novel and progressive solutions are required in microwave field. For example, Fixed Wireless Access concept emerging with the 5G technology requires multi Gb\s data transmission [1]-[3]. In addition, automotive radars for the development of smart roads and vehicles, high resolution body scan and Foreign Object Debris Detection Radar (FODR) applications require transmitter and receiver systems with large operational bandwidth [4]-[7]. By taking advantage of millimeter-wave frequency band, minimization of systems and large operational bandwidths are achievable.

As a consequence of millimeter-wave signal utilization, spacing between elements in an antenna array would be decreased. At W-band frequencies, the spacing between antenna elements in an active electronically scanned array (AESA) would be comparable to the MMIC size. Considering this study, dimensions of the transmitter flip-chip is 5.9x6.7mm while the wavelength is in the order of millimeters at W-band. Hence, the most feasible and efficient solution is to combine MMIC flip-chip and antennas in the same structure such as antenna in package (AiP) [8]-[9].

The main purpose for an AiP concept is to obtain a fully functional package that contains T/R chip, antennas and necessary components such as DC connectors or passive SMD devices. Since measuring performance of an antenna integrated package requires complex test configuration such as an anechoic chamber system, it is required to verify electromagnetic design of the package and RF performance of vital discontinuity locations. For instance, SiGe flip-chip to package transition through C4 solder ball, microstrip and stripline via transitions should be designed carefully in W-band while regarding minimization of the structures to meet high density signal routing.

This study concentrates on the selection of the package technology and electromagnetic designs of the mentioned discontinuity regions. In the end, on-wafer and on-package RF measurements are to be compared.

II. Selection of the Package Technology

As related works are studied, ceramic based low temperature co-fired ceramics (LTCC) and organic substrate based printed circuit boards (PCB) shine out [10]-[11]. The main constraints determining the package technology are operating frequency and interface properties of the SiGe flip-chip. Regarding the operating frequency, substrates used in the package should have stable dielectric constant and low tanδ at W-band. Furthermore, manufacturing capabilities of the selected technology should meet high density signal routing requirement.

In this study, a single transmitter MMIC element consists of approximately 200 C4 solder balls and 16 independent W-band front-ends. In order to obtain a scalable antenna array, the high frequency package could only be built up vertically since planar dimensions are determined by the array size. In other words, the technology should support vertical transitions with a multilayer structure. In addition, manufacturing limits and tolerances should provide fine resolution to the C4 interface properties. For example, distance between adjacent C4 solder balls are 225 μm. As solder and solder mask limits are taken into consideration, PCB technology provide better precision and repeatability for mass production than LTCC.

For the future consideration, antenna integration into the package is another difficulty. In addition to the structural compatibleness, antenna design and integration into the package should be analyzed in depth. The major and predominant factor is the relative dielectric constant of the material. Commercially available PCB and LTCC substrates that would support W-band signals have εr=3 and εr=7.8, respectively. Lower the dielectric constant is, higher the radiation efficiency would be. Therefore, PCB technology provide a better environment in terms of W-band signal transition, SiGe flip-chip with C4 solder ball interface and antenna integration.

Even though PCB manufacturing capabilities seem to be sufficient to design such a package, vertical via transitions in terms of W-band shielding and supply voltage connections could not be achieved in chip dimensions as common via technique is used. In Fig. 1, through via structure is shown. Despite having multilayer structure, vias are extended from bottom to top layer. Hence, efficiency of the area utilization in each layer is drastically reduced. Rather than extending vias unnecessarily, by using stacked via technique shown in Fig. 2, connection between each layer is provided individually.

Therefore, without occupying redundant layers, both RF and DC signal transmission is provided in an efficient way. In this study, 5+N+5 type high density interconnect (HDI) PCB is realized. That is, 5 prepreg materials are used above and below a core substrate resulting a total of 12 conductor layers with providing inter-layer connection using μvias.

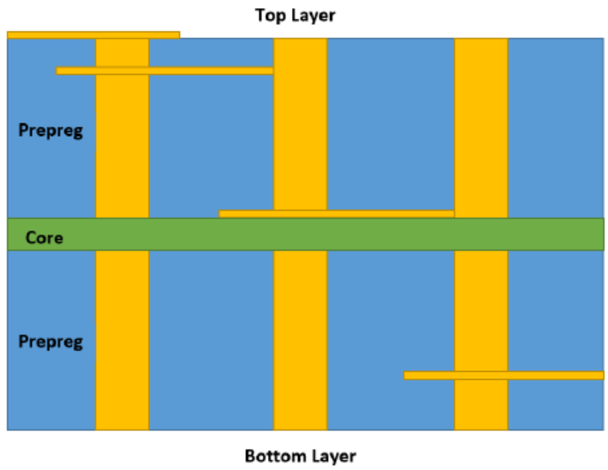

Fig. 1. Through via inter-layer connection technique

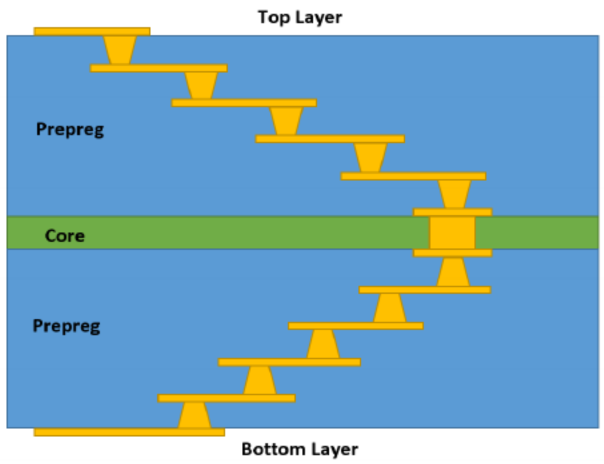

Fig. 2. Through via inter-layer connection technique

III. Electromagnetic Design of the Organic Package at W-Band Frequencies

High density packaging concept proposes a solution to system miniaturization regarding the RF and DC transmission of the SiGe flip-chip at W-band. However, electromagnetic design becomes more complex since it involves different considerations such as flip-chip to PCB transition and antenna array design. In addition to W-band signals, there are many different signals which requires special treatment such as DC supply voltages, TTL control voltages, intermediate frequency (IF) and reference signals. Altering any of these connections would require major revision in multilayer PCB structure. Hence, W-band signal transitions from flip-chip to inner layers of PCB are designed while optimizing required volume and return loss. By designing W-band transitions first, we make sure that W-band structures are kept unchanged during the package construction.

In this section of the study, package modelling and electromagnetic analysis conducted in CST Studio Suite is to be explained.

A. *Flip-Chip to Stripline Transition*

SiGe flip-chip contains 16 RF-front ends. Majority of the W-band channels located in the inner regions while remaining channels are close to edge of the flip-chip. Therefore, two different transition analysis should be conducted for interior and edge regions in W-band.

1) *Corner Region Analysis*

In Fig. 3, electromagnetic model of the W-band transition from flip-chip to stripline in PCB is shown including C4 solder balls. As SiGe flip-chip is inspected, it is seen that metal density on the solder side is high. Instead of modelling the surface of the flip-chip with μm resolution, it is accepted as a perfect electric conductor. The main reason is that order of μm is neglectable as wavelength of the 94 GHz center frequency is considered.

Shape of the C4 solder balls are shaped considering the inspection after assembly to the package. Solder balls are modelled by using lead material shown as purple color while flip-chip surface is shown as gray. Prepreg material is demonstrated as transparent blue while copper is yellow.

In Fig. 4, S-parameters are given after optimizing the matching while keeping size of the structure minimum. It is seen that between 80 – 110 GHz, return loss is lower than 18 dB while active operating region of the flip-chip is better than 20 dB centered around 94 GHz with 0.4 dB insertion loss.

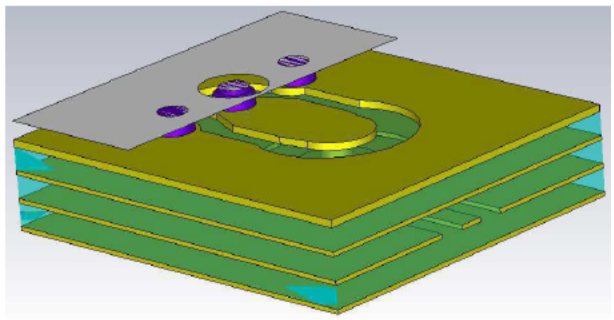

Fig. 3. Model of the flip-chip to stripline transition for edge part

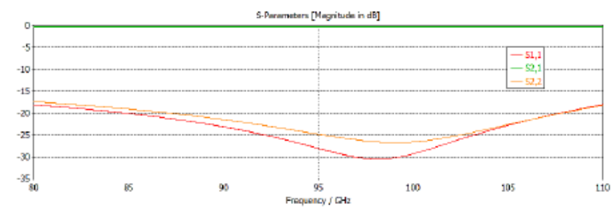

Fig. 4. RF matching performance for edge part analysis

2) *Interion Region Analysis*

As seen in Fig. 3, W-band signal is not directly routed through the PCB since placing vias under C4 solder balls are undesired in terms of matching performance and assembly reliability. Therefore, signal is routed in co-planar grounded wave (CPGW) structure. That is, signal matching would be distorted due to the flip-chip existence in the air. The affect is neglectable for edge part analysis, however, interior part analysis requires further interest.

In Fig. 5, interior part transition from flip-chip to stripline is shown. In Fig. 6, it is seen that length of the both CPGW and stripline structure are increased under the distortion of

SiGe, which is modelled as perfect electric conductor, to obtain fine matching performance.

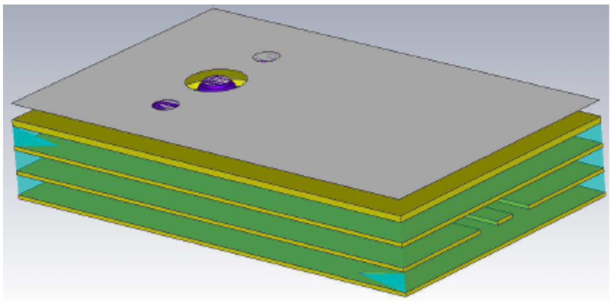

Fig. 5. Interior part of the flip-chip to stripline transition

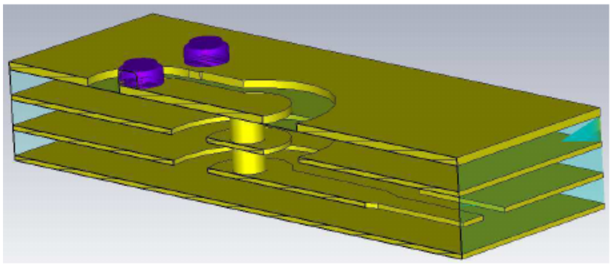

Fig. 6. Half-cut view of the interior part of the flip-chip to stripline transition

In Fig. 7, RF matching performance is given. Similar to previous analysis, below 20 dB return loss and 0.45 dB insertion loss are obtained throughout W-band and optimized around 94 GHz center frequency.

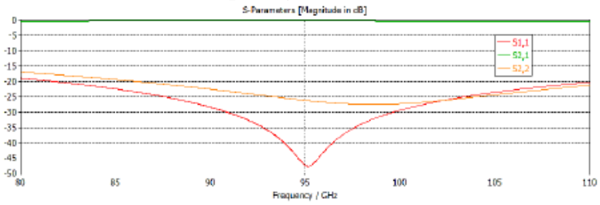

Fig. 7. RF matching performance for interior part analysis

B. RF Probe Transition

In Fig. 8, co-planar grounded wave structure to RF probe matching transition model is given. 50-ohm characteristic impedance of the CPGW line is increased so that RF probe could be landed without short circuiting through ground plane.

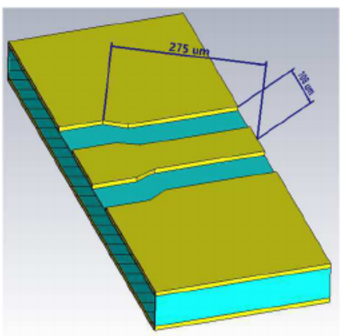

Fig. 8. 150 μm-pitch RF probe measurement structure on PCB

IV. High Density Organic Package Assembly

By using the designed electromagnetic structures, 5+N+5 HDI PCB is manufactured. In Fig. 9, measurement configuration of the high-density organic package with assembled SiGe flip-chip is demonstrated. In addition, DC supply voltages and control signals are connected to bottom of the package through copper wires. Furthermore, relatively low frequency IF and reference signals are given through surface mount SMP type connectors. As seen from the left most part of the package, 150 μm-pitch probe measurement structures are placed. There are four different W-band outputs from flip-chip. Half of them are directly routed in co-planar grounded wave mode while other half is routed inside package in stripline mode. In other words, interior front-ends requires stripline routing while edge front-ends have only co-planar grounded wave structure.

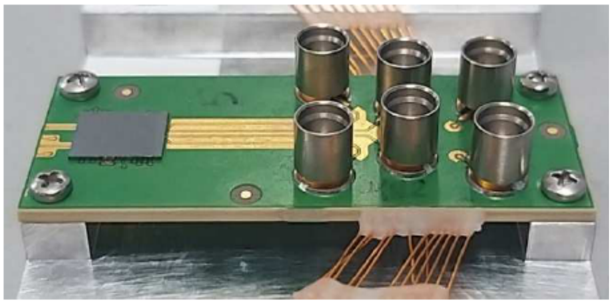

Fig. 9. RF probe measurement package of W-band SiGe flip-chip with low frequency RF and DC connectors

In Fig. 10, RF probe landing on optimized CPGW structure view is shown under microscope.

Fig. 10. RF probe landing on package under microscope during measurement

W-band measurement configuration includes two signal generators for 1 GHz reference and 10 GHz IF signals. Also, an FPGA is utilized to communicate with MMIC. Measured W-band signal is supported by waveguides through the W-band attenuator and down-converter connected to spectrum analyzer. RF cable, W-band probe, waveguide and mixer losses are added to spectrum analyzer result to calculate the 10 GHz IF to 94 GHz signal gain of the flip-chip.

V. RF PROBE MEASUREMENT CONFIGURATION IN W-BAND

On-chip and on-package measurements are compared for a transmitter SiGe flip-chip. In Fig. 11, on-chip measurement view with custom-made RF and DC probes are shown. On-chip test results are:

- Small signal gain is between 30 – 35 dB in 92 – 96 GHz band
- 7 dBm saturation power at 94 GHz

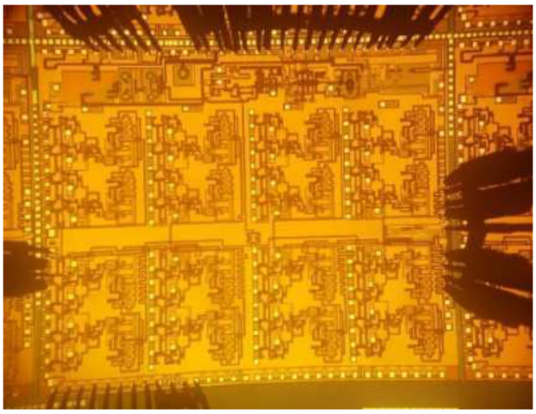

Fig. 11. On-chip measurement configuration

In Fig. 12, gain with respect to frequency graph is given. Different channels shown in Fig. 8 are measured. By taking package measurements, we observe how design is affected from manufacturing capabilities of different companies, effect of C4 solder balls, assembly process and electromagnetic modelling. It is seen that average gain 30 – 35 dB is achieved in active operation band.

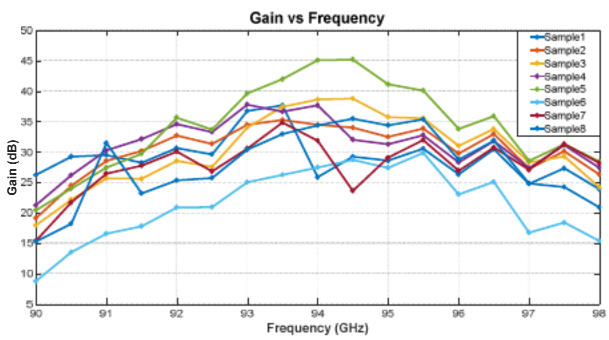

Fig. 12. On-package gain measurement in W-band

In Fig. 13, output power with respect to input power is given. Even though there exist a difference in small signal stage, output power is saturated around 7 dBm at 94 GHz. Only one sample separated from others in terms of saturated power is seen to have gain below 30 dB throughout the band in terms of gain seen in Fig. 12. The reason of deteriorated performance could be resulted from assembly process of flip-chip or manufacturing tolerances of the PCB.

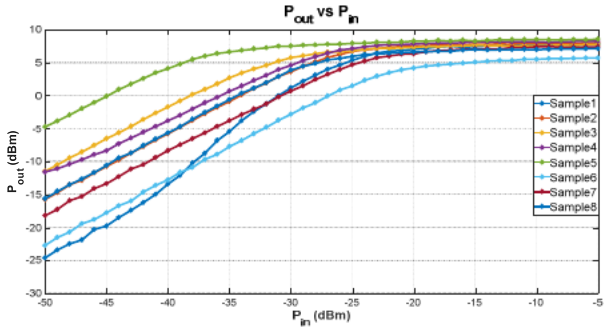

Fig. 13. On-package measurement P_{out} vs P_{in} at 94GHz

VI. CONCLUSION

In this paper, high density packaging concept of a SiGe flip-chip on a multilayer organic package operating around 94 GHz center frequency is explained. Electromagnetic modelling of interaction between flip-chip and PCB, C4 solder ball, via transitions considering minimum volume and W-band RF probe measurement structure are represented in detail. On-chip and on-package measurements show consistency which means that electromagnetic modelling via CST Studio in W-band verified. By using W-band transition structures conducted in this work, antenna implementation to the package becomes feasible for the antenna in package concept for the future work.

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