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Novel Composite RF PCB Stack-up & Engineering for Wideband RF Cross-Overs

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***Abstract*— A Novel Composite RF PCB Stack-up which is simple, economical & manufacturable is proposed and realized. Paper also discusses design & engineering of wide band (DC to 18GHz) RF transitions and routing of RF traces in inner layers of proposed composite multi- layer printed circuit boards (PCB's) with minimum losses. Design is suited for Microwave Integrated Circuits (MICs) based applications involving multiple RF crossovers realized on single composite RF card. Design considers two traces, one direct & other transiting trace for RF crossover. The transiting trace undergoes through multiple changes in RF medium at junctions namely a) CPW/Micro-strip to Coax, b) Coax to Strip-line c) Strip-line to Coax d) Coax to CPW/Micro-strip. To ensure minimum insertion loss over required frequency band, key challenge is to provide better matching at the transitions. The Stack-up that is proposed is realized for 6 layers. RF traces are routed in 1st & 3rd layers. A straight RF trace is printed on 1st layer & is compared with transiting RF trace of similar length. Though the work can be extended to more number of RF buried layers. Topology planning, design considerations, engineering, result analysis are discussed in this paper.**

Index Terms --- RF cross-overs, Composite RF PCB Stack-up, Direct Trace, Transiting Trace.

I. Introduction & Proposed Stack-up

The requirement for compact, lightweight and multifunctional sytems for Radar, Communication, EW, SATCOM etc. is the current need. This in turn require robust RF subsystems realized in small real estates. Typically, they are receivers, transmitters, up-converters, down-converters etc. that may feature multi-channel, multi-I/O and multi-functionality. Traditional design consisted of separate RF card and Power supply & control card. RF card were realized on one side of deck and PS and control on other side of deck.They were connected using enamel wires or feed throughs. If any RF connection is to be done from top to bottom deck then RF cables are used or Coax type transition using Teflon bush and pin are planned for RF transition [1-3]. As there was need for compact designs, RF signals and supply traces were realized on same composite card. Typically RF circuitry and some supply circuitry were realized only on top most layers and other layers were dedicated only for routing supply & control signals [4]. Typical layer stack of these type of RF composite board is shown in Fig-1. Where Substrate-A is suited for realizing RF traces which are bonded to multiple economical Substrate-B to realize control & supply traces in inner layers.

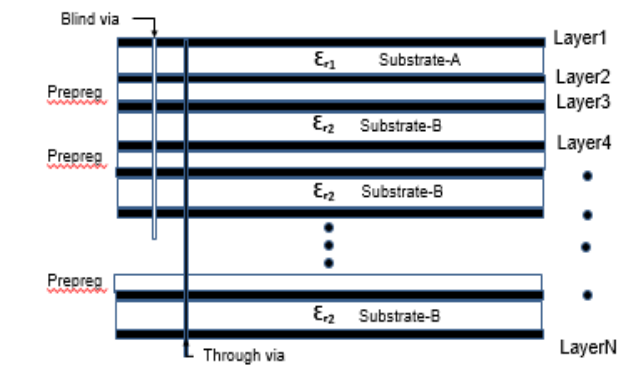

Fig-1 Traditional RF Composite multilayer Stack-Up

Need for multichannel, compact multifunctional wideband RF operations results in 2 or more RF layer designs, and leads to approach for hybrid composite boards capable to carry wideband RF signals along with supply & control signals. DC or low frequency cross-overs can be easily done by routing traces in multiple layers and connecting them with normal vias. But same principle is not true for RF (high frequency, high speed data traces) cross overs. Impedance matching over wide RF frequency range at transitions [5] is very critical for good RF cross-over designs. To achieve it, various solutions are available [6-7]. For high frequency RF traces, the transitions planned is microstrip – coaxial – stripline- coaxial –microstrip for efficient energy transfer with minimum losses [8-9].

The design for a wideband RF transition in a composite multilayer board arrangement calls for a layer stack-up that offers optimal condition for wide band signals to flow with minimum losses (matched impedances at each transitions). Proposal-1 is a possible solution of realizing required layer stack-up shown in Fig-2.

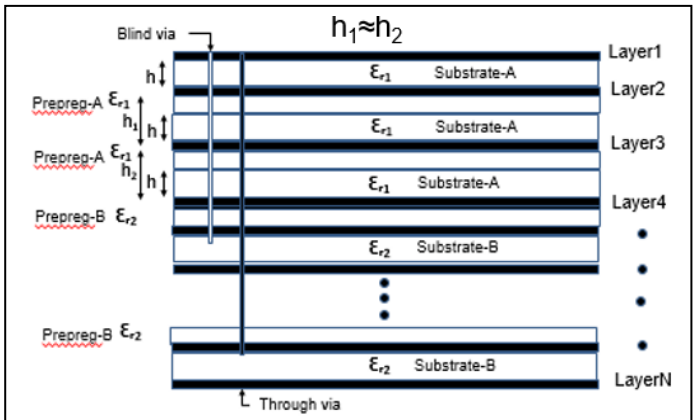

Fig-2 Proposal-1 for multiple RF layer Composite Stack-Up

Here layers 1&2 and layer 3&4 realized on same dielectric laminates in combination with prepreg suitable for RF designs (dielectric constant ε_{r1}, substrate-A & prepreg-A). Substrate-A chosen such as it is ideal to handle supply, controls & RF signal with minimum losses, (low loss tangent). Layer 1 & layer 2 are formed on substrate-A with height h. Layer 1 is used to realize RF trace as a micro-strip, cpw or cpwg. Layer 2 is realized as a ground reference for Layer 1. Layer 3 & layer 4 form by binding combination of substrate-A & prepreg-A such that layer 3 sees ground layers realized in layer 2 & layer 4 at height h. (suitable condition to realize symmetric strip-line). Here strip-lines can be realized in inner layers (layer-3 and above) and are connected by blind signal vias . Blind signal via's always runs to even layers for simple and cost efficient fabrication process.Stack-up proposed in Fig-2 is ideal to realize symmetric stripline, but it is realtively expensive as more number of RF substrates are used in comparision to Proposal-2.

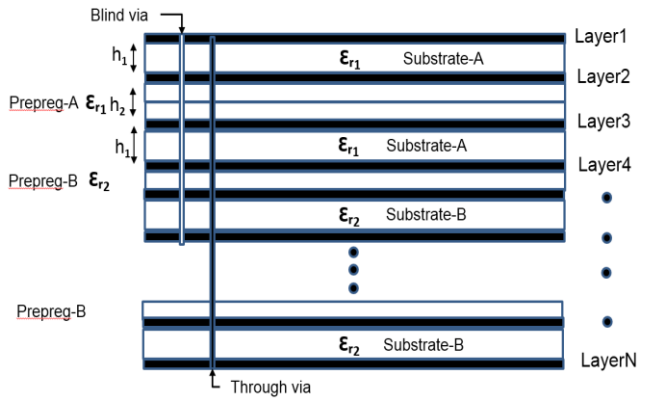

Fig-3 Proposal-2 for multiple RF layer Composite Stack-Up

Another stack-up solution Proposal-2 that is simple, cost-effective, flexible & logical to route RF traces in inner layers is shown in Fig-3[10]. Here multiple sheets of prepegs are forged such that height of substrate and prepregs are similar i.e. height ($h_1 \approx h_2$). This is optimal condition for layer 3 to be realized as stripline (TEM mode) for signal flow with Layer 2 and Layer 4 as reference ground for traces realized on Layer3. Only drawback is control over maintaining height h_2 is difficult which results in realization of assymetric stripline structures in inner layers. This configuration for layer 1 to layer 4 can be extended to further layers to realize more buried RF layers. The rest stack up is for routing only controls & supply signals, by sandwiching less expensive dielectric laminate ε_{r2} (substrate-B) and relevant prepreg with dielectric constant ε_{r2}. Blind vias are used for routing and distribution of supply, controls & RF signals between Layer 1 & other inner layers. Through vias are used to connect RF & digital ground references for all layers.

II. Module Design & Simulation

A six-layer board is modelled in 3D EM simulator in line with proposal-2 stack-up as shown in Fig-4 [10]. Here, signal traces (direct & transition traces) are realized in layer 1 & layer 3, and is connected by blind vias. Layers 2, 4, 5 & 6 are ground layers. Layer 1 to 4 are realized on substrate-A with εr =3.5 and is suitable for RF designs. Layer 5&6 are realized on substrate-B with εr =4.7 and these substrates are more economical in comparision to substrate-A. This in turn makes entire stack-up economical compared to realizing all layers on multiple fused substrate-A stack-up. Though the work can be extended to more number of layers & substrates.

Layer 1 the trace can be realized as a microstrip, cpw or cpwg. In proposed model the direct trace and transition traces are routed in layer1 as seen in Fig-5. A to B is direct trace. The transition trace is C to D, which is combination of C to E , E to F and F to D. C to E, F to

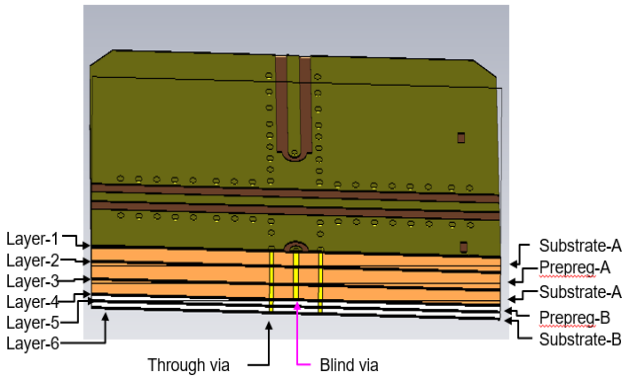

Fig-4 Six layer 3D EM model in line with proposal-2

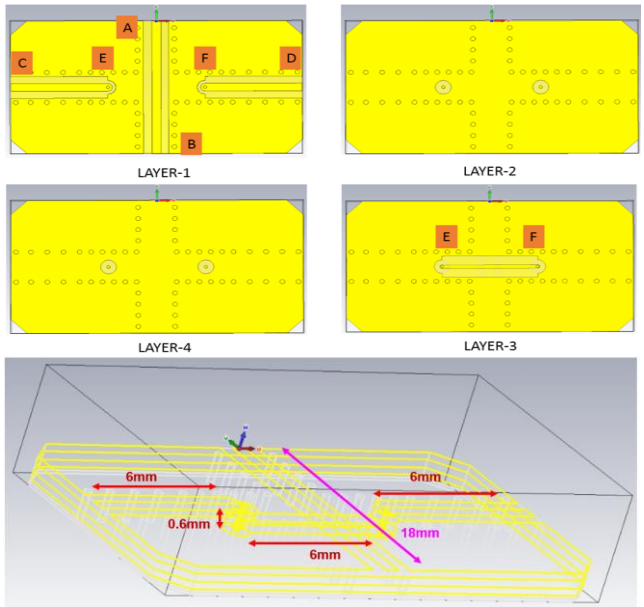

Fig-5 Traces routed in first and inner layers, & wireframe 3D model

D is realized on layer-1 and E to F is realized in layer-3. Transition from layer1 to layer3 is by blind via which extends upto layer4 considering ease of manufacturability. Trace A to B is effectively 18mm and Trace C to D is effectively 19.2mm (approx.). The transiting trace goes through multiple transitions namely a) Micro-strip to Coax, b) Coax to Strip-line c) Strip-line to Coax d) Coax to Micro-strip.

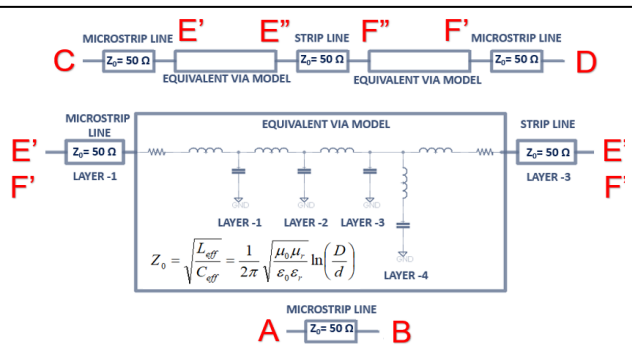

Fig-6 Equivalent model of tranisting and direct traces

The equivalent model of the direct and transition traces is shown in Fig-6. In present case, the direct path impedance is governed by standard equations for micro-strip line [11]. Strip-line realized in inner layer is asymmetric due to difficulty in maintaining height ($h_1 \approx h_2$) as in Fig-1 and hence impedance is governed by Eq-1. [10]

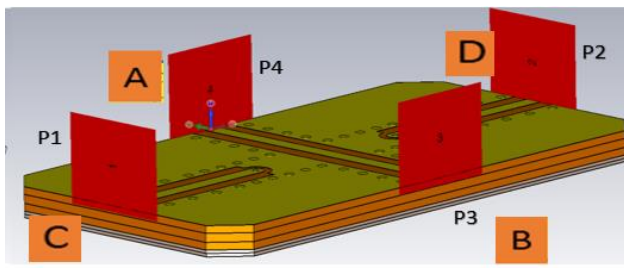

Fig-7 3D EM model of proposed stack-up indicating simulation

$$Z_0 = \frac{80}{\sqrt{\varepsilon_r}} \ln\left(\frac{1.9(2h_1+t)}{0.8w+t}\right)\left(1-\frac{h_1}{4h_2}\right) \quad (1)$$

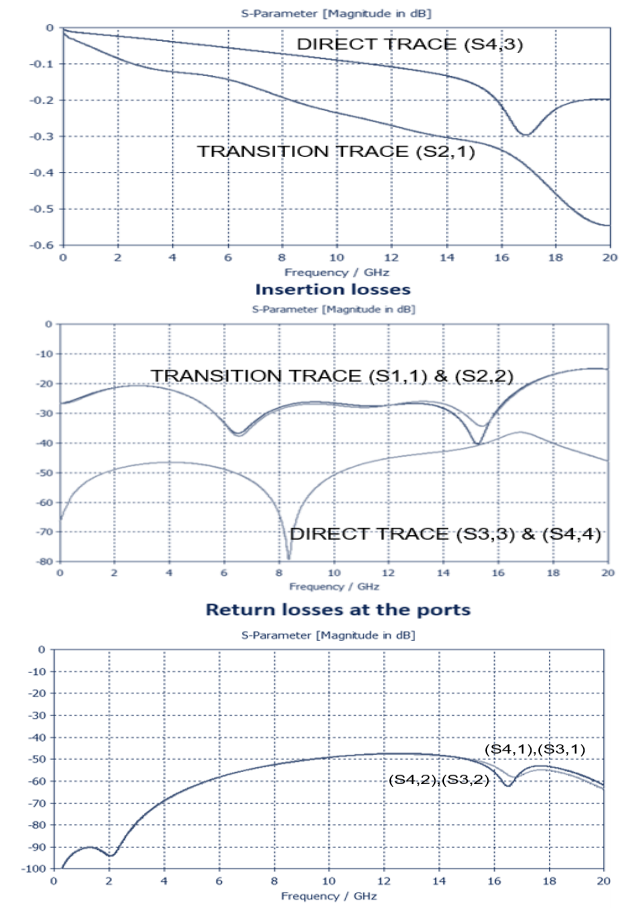

Fig-8 3D EM model simulated results

The micro-strip trace & strip-line trace is connected by blind vias and the equivalent model is seen in Fig-6. The blind via has ground

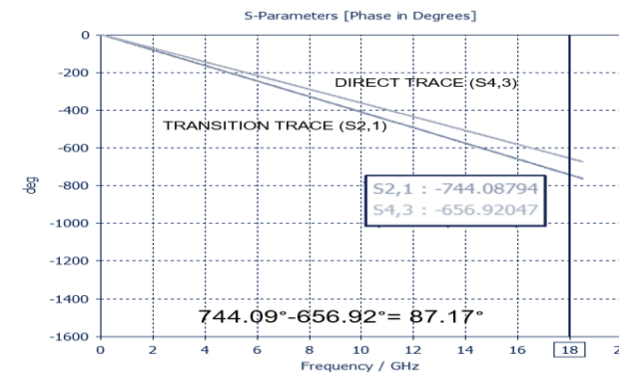

Fig-9 Unwrapped Phases of simulated 3D EM models

clearance in each layer to realize coaxial transmission line, whose impedance is governed by Eq-2 [10].

$$Z_0 = \sqrt{\frac{L_{eff}}{C_{eff}}} = \frac{1}{2\pi}\sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}}\ln\left(\frac{D}{d}\right) \tag{2}$$

3D EM model of proposed 6 layer composite stack-up is seen in Fig-7[10]. The simulated insertion losses, return losses & isolation between direct and transition traces of the 3D EM model is shown in Fig-8 [10]. We can conclude from plots that design is made for minimum insertion losses and return losses >15dB over entire band of interest. Isolation >45dB is ensured in simulations over entire band of interest. The simulated unwrapped phases & difference between traces is seen in Fig-9.

The Phase in the medium is governed by Eq-3, where $\Delta\phi$ is phase difference, ω is angular frequency, L_{TL} lenth of transmission line, v_p is phase velocity and ε_r relative dielectric constant of medium.

$$\Delta\phi = \frac{\omega L_{TL}}{v_p} = \frac{\omega L_{TL}\sqrt{\varepsilon_r}}{c} \tag{3}$$

Phase difference between the traces at 18GHz is approx. equals to 87.2° which is due to difference in path length of direct and transition traces by 1.2 mm. (Two via tansitions) & variation in medium for transition trace.

III. Module Development & Measured Results

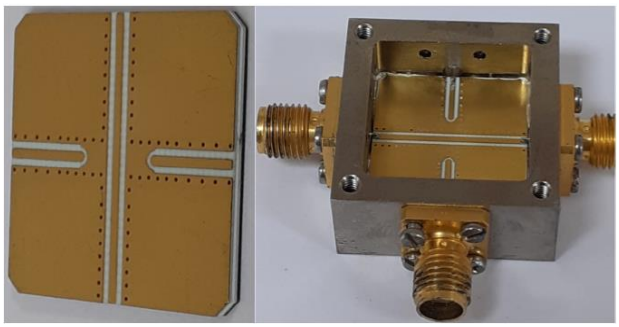

Fig-10 Manufactured PCB and mechanical enclosure for testing

The manufactured 6-layer PCB is shown in Fig-10. Here two Rogers RO4350 materials are used for RF layers and is backed by FR4 to form composite multilayer board. RO4450 is used as binding material. Testing enclosure is also shown in Fig-10 with connectors for testing of this multilayer PCB.[10]

The measured results of the manufactured 6-layered composite PCB can be seen in Fig-13. [10] It can be inferred from measured results that insertion loss of <3.2dB up to 18GHz for transiting trace in comparison to insertion loss of <2.9dB for direct trace. Minimum isolation of 40dB is achieved over entire desired band of operation. Return losses of both the RF traces are >10dB. The unwrapped phase of measured direct and transition traces are plotted in Fig-12. Here we can observe that the phase is linear for both the RF traces and at 18GHz we can see the phase difference between two traces is close to 78.05° (This phase difference is almost similar to that of simulated 3D EM model). Thus we can conclude that there is a close correlation between the measured & simulated results. Additional phase of 700° is introduced in both traces as compared to simulated results & it can be accounted due to inclusion of connectors at both end of each traces.

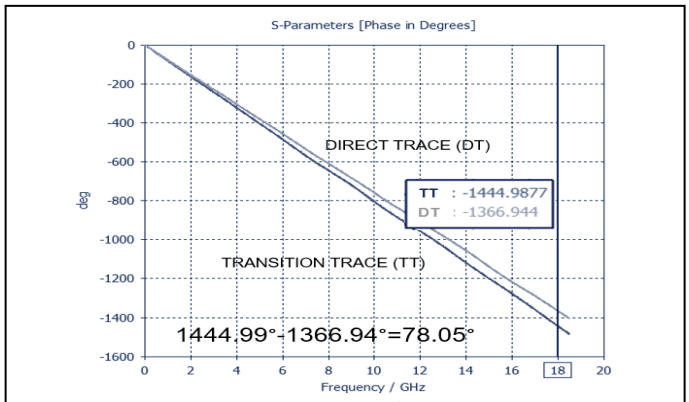

Fig-12 Unwrapped Phases of measured result

The detailed analysis of simulated & practically achieved results are dealt in next section of this paper.

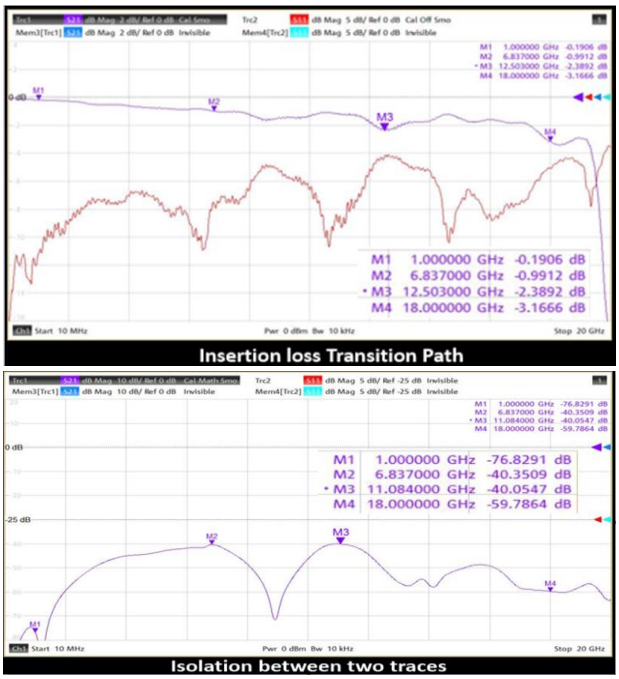

Fig-13 Practically measured result of RF crossover on 6 layer PCB

IV. Post Result Analysis

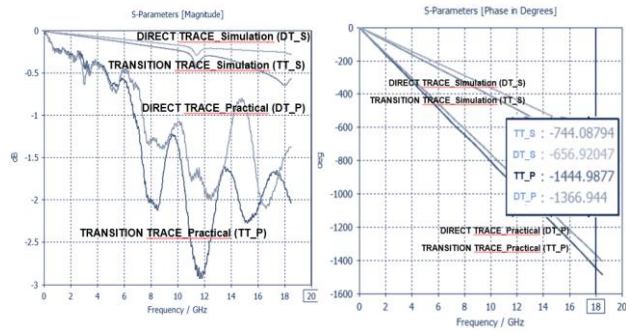

Fig-14 Comparision of simulated & measured results

There is a difference between simulated & practically achieved results are seen in Fig-14. There is degradation in insertion loss in practical case and also more phase is introduced in both the traces at 18GHz. The additional insertion loss & phase can be attributed to reasons such as use of SMA connectors in practically realized module to test the proposed design. The two connectors on each trace introduces additional insertion loss and phase. Extra electrical length seen in Fig-15 is additionally introduced in path due to use of SMA connectors that results approx. addition of 700° phase added in practical case as compared to simulated phase at 18GHz calculated using Eq-3.

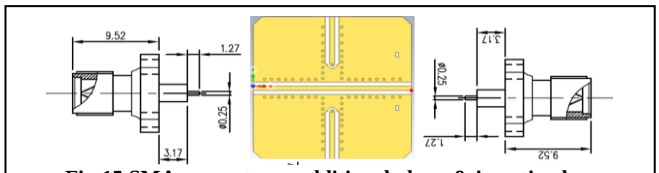

Fig-15 SMA connectors - additional phase & insertion loss

Besides other possible reasons are mismatch of impedance at each transition, misalignment of blind via resulting in improper coaxial transition as seen in Fig-16, manufacturing tolerances not maintained resulting in realization of asymmetric strip-line in buried layers, no edge plating of designed PCB (critical- for stitching ground references at boundary for smooth RF transfer) compared with edge plated PCB is seen in Fig-16, also contribute to degraded insertion loss. Efforts to be made to address these. There is a good correlation between the simulated and practical results as seen. Also, the phase linearity is maintained, thus finds applications where multiple RF cross-overs are present and were phase linearity matters.

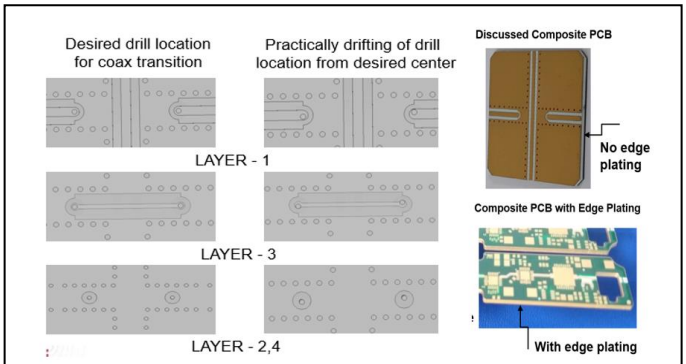

Fig-16 Misalignment of blind via & Edge plating Issue

V. Conclusion

Novel Composite RF PCB Stack-up which is simple, economical & manufacturable is proposed. Paper discusses design & engineering of wide band (DC to 18GHz) RF transitions and routing of RF traces in inner layers of proposed composite multi- layer printed circuit boards (PCB's) with minimum losses. Solution for RF criss-crossings and crossovers are discussed. Proposed PCB stack-up and broad band RF transition has been designed, simulated and practically realized. Insertion loss <3.2dB up to 18GHz for trace length of 18mm, minimum isolation of 40dB over entire band and return losses of both the RF traces >10dB has been practically achieved. Phase linearity is maintained over entire band and phase difference between traces are almost identical for measured and simulated results. Measured result show satisfactory correlation with simulated results and it is promising for MIC's based applications where multiple traces cross each other. Further the hybrid PCB stack-up can be used in design of various subsystems for RADAR, EW, SATCOM etc. applications. Edge plating of PCB is a key learning from this work for efficient transfer of RF energies. Future scope of work is to minimize the losses, achieve higher isolation and minimize phase difference among the traces.

Acknowledgment

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