

Full-wave Analysis and Characterization of RF Package for MEMS Applications

Ayan Karmakar, Kamaljeet Singh

Abstract - This article details about package analysis of RF-MEMS based devices for Ka-band applications. Standard cavity package has been taken into consideration. FEM based electromagnetic solver Ansys HFSS suite is utilized for this purpose. Constraints related to Ka-band and its possible remedies are discussed. Eigen-mode analysis and loss characterization have been done using HFSS. Possible causes of RF losses at 30 ± 1 GHz have been investigated. Further, new package configuration with recommended features, yielding better simulated RF performances is presented in this work. Practically, the package has been characterized.

Keywords - Cavity package, Bond wire, Eigen mode and transition.

I. INTRODUCTION

A significant progress in design and fabrication process for MEMS (Micro Electro Mechanical System) technology has been observed in the last few decades. But, the only bottleneck of this new technology is its packaging topology directing towards reliability constraints. Unlike the other microelectronics (VLSI/ULSI) devices, the specialty for MEMS packages is to support free-hanging mechanical tiny structures. Usually, the main functions of packages are: providing mechanical support, protection from surrounding environment and building electrical interconnection to other system components [1-3]. Traditionally for many years, RF devices have been packaged in metal-can, ceramic and cerdip cavity packages. Among these, cavity packaging for the RF is most proffered in the consideration of providing headspace for raised surface features, such as air-bridges and protects elements such as RF MEMS switch, Phase Shifter, filter, resonators or any reconfigurable devices, etc [4-8]. The present work primarily demonstrates a standard cavity package modified for RF MEMS application. This article also highlights various approaches adopted to mitigate losses introduced in its assembly working at Ka-band.

Along with the insertion and dielectric losses associated with the circuit, radiation losses also come into picture predominantly at this higher side of microwave band.

An FEM based simulation study is carried out for this whole research work. Contribution of each building block has been investigated in detail and further complete loss analysis is accomplished.

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II. PACKAGE CONFIGURATION

The package consists of –Transition for RF launching, six numbers of DC feedthrus, DUT block and two numbers of RF connectors at input and output sides. The photograph of the standard cavity type package under consideration is shown in Fig. 1. The internal package cavity has a dimension of 13.5 mm (length) $\times$ 9 mm (width) $\times$ 8 mm (height). Detailed EM analysis of the package is described in the subsequent sections.

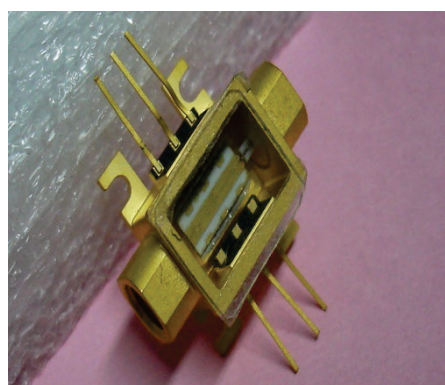


Fig. 1. RF package for MEMS application (Courtesy: Kyocera)

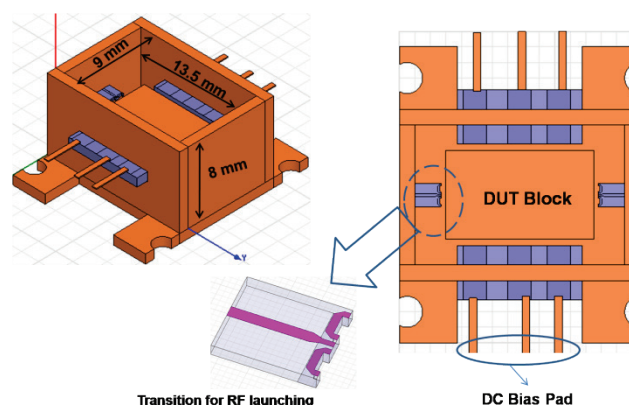


Fig. 2. Geometry of the RF Package built in HFSS

III. PACKAGE SIMULATION

The complete analysis may be categorized broadly in two parts: One, eigen-mode simulation and second, loss characterization. Both the simulation activities have been carried out with the aid of HFSS solver [15]. The 3D structure of the package is shown in Fig. 2. The following subsections will detail eigen-mode simulated results and the complete loss characterization. Finally, a modification in the standard package is suggested to have optimum characteristics.

A. Eigen-mode Simulation

Like other MEMS sensors, RF-MEMS based devices also require a hermetic environment, free from unwanted dust particles, any kind of force/field for its faithful operation. Package enclosure tries to provide all these features. But, in RF-domain physical dimension of the package also plays an important role to alter the overall performance of the device. It happens particularly while the resonant mode of the internal cavity of the package gets excited [9]. Eigen-mode simulation is carried out to predict this phenomenon. In present case, analysis is carried out at 30 ± 1 GHz. The internal package cavity dimension is 13.5 mm (L) $\times$ 9 mm (W) $\times$ 8 mm (H), as shown in Fig. 2. This results in resonance frequency of 33.4902 GHz. Table 1 summarizes the Eigen-mode simulation result of the package with different conditions. The presence of dielectric materials (such as feed thru, chip and other interconnect lines) known to be detrimental for resonance situations, was taken into consideration during this analysis. Fig. 3 shows the spatial variation of electric field inside the cavity at the resonance condition.

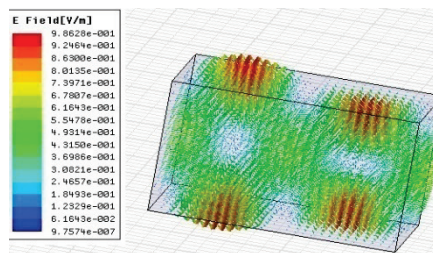


Fig. 3. Simulated electric field variation inside the package cavity

TABLE 1
EIGEN-MODE ANALYSIS OF THE PACKAGE

Structure Details	Frequency (GHz)
Empty cavity	33.4902
DUT Block inserted	30.4706
One DC feed thru added	30.1336
Three DC feed thru added	30.1333
RF feed Thru added at Input	30.1333
Both RF feed thru added at Input and Output ports	30.1322

Generally the top-side cover is recommended to be placed above the DUT at least at a height of ten times the substrate thickness [1]. In the present work, the top cover is placed 2.3 mm above the DUT block, whereas the substrate thickness of the device is 10 mil ($\sim 254 \mu\text{m}$). The side-walls through which DC feed thrus' are launched, usually are placed quarter-wavelength (at operating frequency) apart from the DUT block.

B. Loss Characterization

Total loss of the packaged device can be categorized as: conductor loss, dielectric loss and radiation loss. Out of these, first two losses can be taken care during design by properly

choosing the substrate height and metal thickness. The third and the most important type i.e. radiation losses associated with the package may be due to following three reasons:

- Transition for launching RF signal,
- Wire-bond used for interconnection purposes. It is very much prone to radiation and noise,
- Gap between the RF transition and DUT block.

All these points are investigated in subsequent sections.

B.1 Transition for RF Launching

In the package under consideration, there is MS-CPW (micro-strip to coplanar waveguide) transition at the RF launching ports. This is to facilitate the testing or characterization of the package with easily available SMA/K-type connectors. Transitions have been made on 10 mil standard Alumina substrate. Chrome-gold layer is used as metallization purpose. Conductor-backed (CB) configuration is used here for the CPW structure. Schematic diagram of the transition is shown in Fig. 4. Simulation study predicts that, this transition structure itself can be responsible for a signal loss of around 0.18 dB at 30 GHz.

TABLE 2
OPTIMIZING THE NUMBER OF BOND-WIRES

No. of bond-wires	R.L (dB)	I.L (dB)
1	-8.24	-3.4
2	-12.4	-2.9
3	-18.9	-2.3
4	-11.9	-2.8
5	-18.9	-2.8

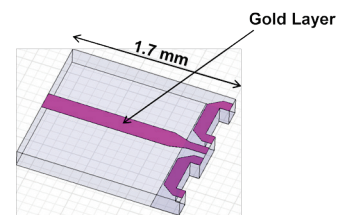


Fig. 4. CPW-MS Transition structure

B.2 Bond-wire Analysis

Wire-bonds are used extensively in packaging technology for chip to package or chip to RF connection bonding purpose. At the higher frequency range, it also has some detrimental effect on the RF performance. It can be thought as a parasitic inductor series with some resistor, if its dimension is shorter than the operating wavelength. When the RF current cycle increases and decreases in a sinusoidal fashion, the magnetic field surrounding a bond-wire expands and contracts, inducing a time varying voltage [1,9-10]. Ideally, bond-wires should be placed one quarter wavelength apart or less, not in arbitrary fashion [1]. Otherwise, their interactive coupling fields may

affect the performance of the device. The skin-depth phenomena also come into picture. So, the dimension of the wire becomes very important. At the frequency above 6 GHz, both the substrate and mutual capacitances play important role. For bond-wire analysis JEDEC standard [13] has been used in HFSS [15]. The inductance of the wire-bond can be evaluated by standard closed-form equations [11-12]. As a rule of thumb, 1 mm long 1 mil wire provides 1 nH inductance.

To optimize the number of the bond-wires needed between RF transition and DUT (Device under Test), parametric simulation study was performed. Fig. 5 shows a generalized schematic diagram of the bond-wire connected package portion and Table 2 summarizes the effect of bond-wire numbers on the actual package with a gap of 0.3 mm. The study assumes that the bond wire is made of gold (diameter = 1mil).

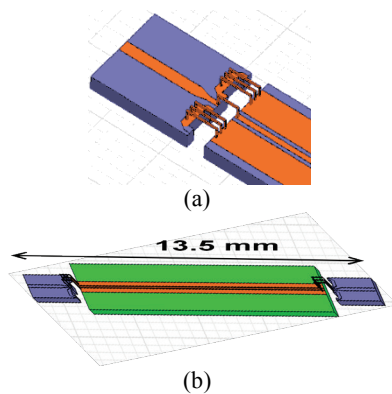


Fig. 5 (a) Generalized schematic diagram showing the bond-wire geometry (b): Zoomed view of the packaged DUT with transitions at both ends and bond-wires associated with the structure

From Table 2, it can be inferred that three numbers of bond-wires are optimum for the transition structure. So, in the final structure we place three numbers of wires at I/O sides.

Conventional wire-bonding technique can't be implemented in the present case, due to non-planarity in the whole assembly along with deep cavity. Deep-access bonding mechanism [14] has been used here.

B.3 Effect of Gap Between the RF Transition and DUT

Standard package under consideration has a gap of 0.3 mm between the transition and DUT at both input and output sides as shown in Fig. 6. This gap introduces a discontinuity from RF point of view, which is major cause of signal attenuation of the entire package. Varying the gap shows the change in the RF performance of the packaged device, as depicted in Table 3.

Study shows that, reduction in the gap dimension in the order of 0.1 mm can result in an appreciable improvement (more than 6 dB) of impedance matching.

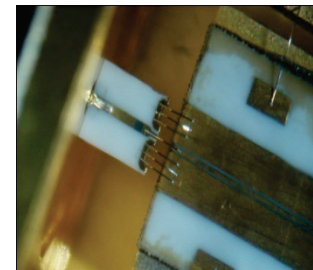
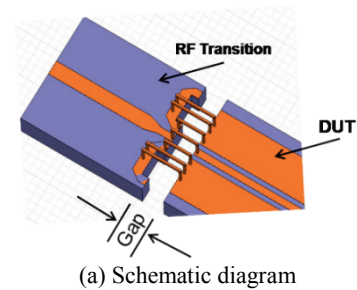


Fig. 6. Gap between RF transition and DUT block

TABLE 3
EFFECT OF GAP ON THE RF PERFORMANCES OF TRANSITION AND DUT

Gap (mm)	R.L (dB)	I.L (dB)
0.3	-18.9	-2.78
0.2	-25.5	-2.70
0.1	-35.3	-2.60

B.4 Complete Loss Analysis

Fig. 7 shows the full-wave analysis of the DUT embedded complete package with all optimized parameters. It shows that, presently the complete packaged device gives an insertion loss of around 4 dB at 30 GHz with an impedance matching of better than 15 dB.

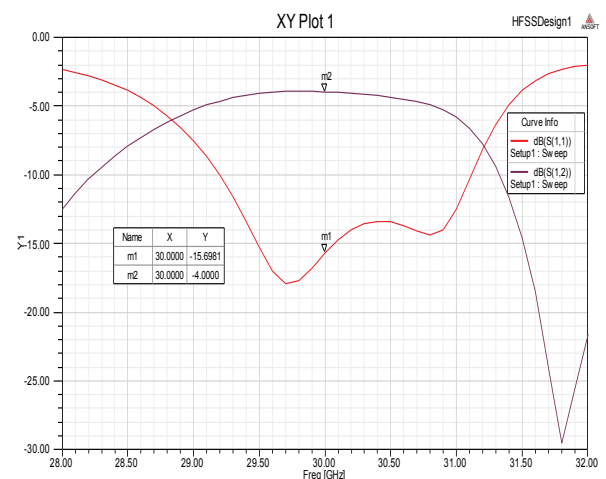


Fig. 7. RF performance of the packaged device

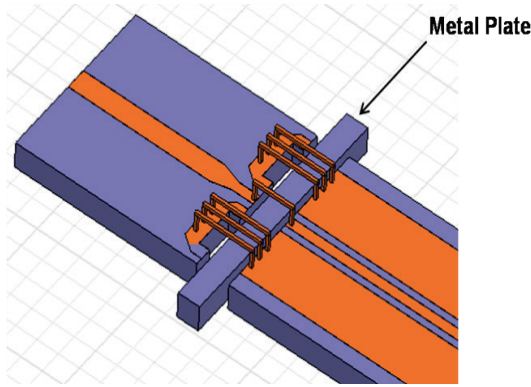


Fig. 8. Schematic overview of the metallic plate embedded transition structure

Significant improvement in the signal loss management can be done by the proposed configuration, as detailed in section C.

C. Proposed Modification

To mitigate the extra insertion losses due to radiation at the junction of RF transition and DUT, metallic slit/plate can be introduced, as shown in Fig. 8. It helps to provide a path for field emanating from the transition point. In fact, it facilitates to smoothen the mode-matching mechanisms between different transmission line structures. Parametric study was performed to freeze the dimension of the metallic block for the aforesaid purposes. Table 4 depicts the effect of metallic plate dimension on the overall performance of the packaged DUT.

TABLE 4
OPTIMIZATION OF METAL PLATE DIMENSION

Length (mm)	Width (mm)	Height (mm)	R.L (dB)	I.L (dB)
1.9	0.2	0.1	-12.4	-2.72
1.9	0.1	0.2	-13.5	-2.50
1.9	0.2	0.2	-16.4	-2.27
2.1	0.2	0.2	-17.1	-2.18

The above analysis shows that, fourth row dimension of the metallic plate is the best to suppress radiation effect. It means a 2.1 mm long, 0.2 mm wide and 0.2 mm high plate should be embedded in the package itself in the radiation prone area. The metallic block will provide a ground path for the unwanted field radiating from the junction point. Significantly, the insertion loss of the whole packaged device has been reduced from 4 dB to 2.18 dB, keeping an appreciable impedance matching characteristic.

The whole package analysis work with the proposed idea is summarized in Table 5. It depicts that, the loss of the whole package assembly can be reduced from 4.2 dB to 2.82 dB with an insertion of the metallic slab like structure in the gap between the transitions and the DUT block. Fig. 9 shows schematically the various sections of the package under consideration.

TABLE 5
SUMMARIZED RF PERFORMANCE OF THE VARIOUS MODULES OF THE PACKAGE

Str.	Structure Details	R.L(dB)	I.L(dB)
1	RF Transition(MS-CPW)	-30.0	-0.18
2	DUT(Tx-line)	-31.5	-0.60
3	Transition at one end + DUT(without any metallic plate in the gap)	-18.9	-2.78
4	Transition + Metal plate +DUT	-17.13	-2.17
5	Transitions at both ends + DUT(without any metallic plate in the gap)	-15.0	-4.20
6	Transitions at both ends + Metallic plates at two gaps + DUT	-16.0	-2.82

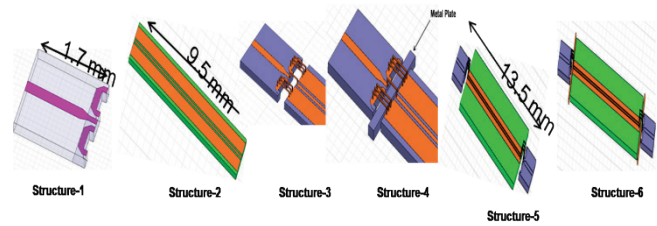


Fig. 9. Various basic sections of the package under consideration, as explained in Table 5

IV. CHARACTERIZATION

Initially a finite ground based co-planar waveguide (FG-CPW) 50 Ω transmission line of 9.5 mm long was printed on Alumina (96%) substrate of 10 mil thickness. Gold (with chromium used as seed layer) is used for the metallization purpose. 2 μ m is kept as metal thickness considering the skin-depth effect at Ka-band. This transmission line structure is mounted on the DUT block and then the package (Fig. 10) is characterized for the frequency range of 29 to 31 GHz. S-parameter results of the packaged transmission line is shown in Fig. 11 and comparative analysis between the simulated and the experimental values is plotted in Fig. 12. Disagreement between the two results may be attributed to dispersive nature [16] of the dielectric substrate, especially in case of return loss plot. The ' ϵ_r ' value doesn't remain constant at Ka-band, but for simulation constant permittivity value is taken. The quasi-TEM or quasi-static approximation may not be valid at Ka-band.

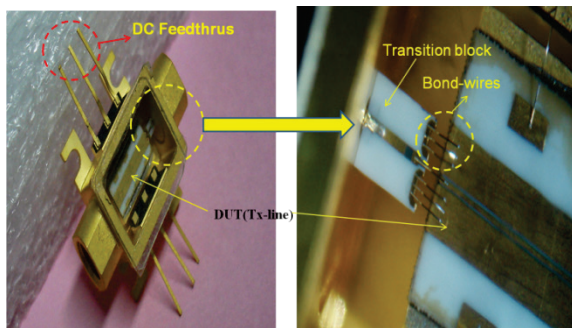


Fig. 10. RF Package with the DUT and bond-wires

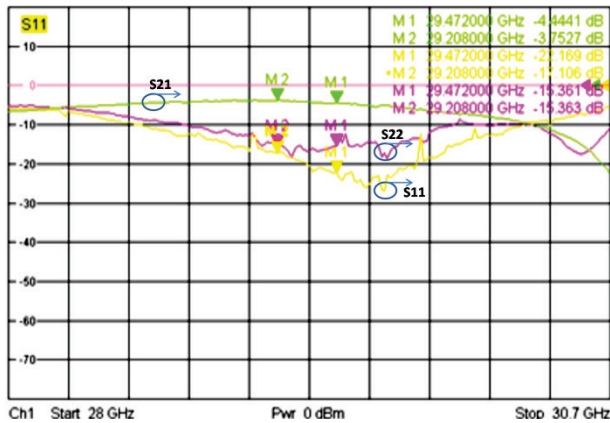
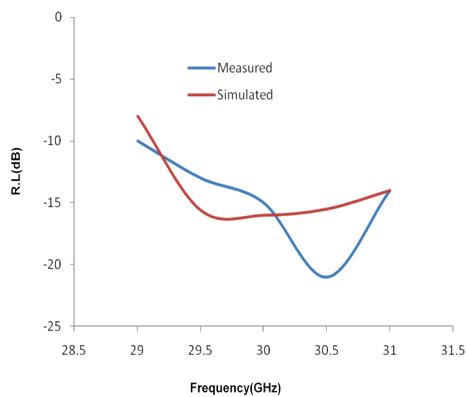
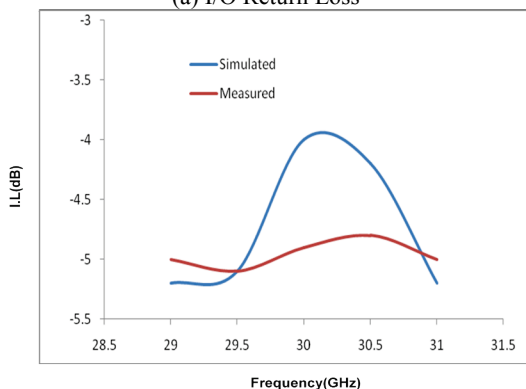


Fig. 11. RF performance of the package in network analyzer



(a) I/O Return Loss



(b) Insertion Loss

Fig. 12 (a) and (b): RF performance of the package

The main attraction of this present work is the simplicity of the structure, which can be implemented very easily. Table 6 highlights the comparison of the current work with already done previous works related to this.

TABLE 6
COMPARISON OF PRESENT RESEARCH WORK WITH PREVIOUS
WORK DONE

Work done	Technology	Freq.	Remarks
[17]	LCP	2-20 GHz	Fabrication criticality for package realization
[18]	Wafer level capping and wafer to wafer bonding	--	Reliability issue related to anodic bonding and wafer thinning process by KOH.
[19]	LTCC-SoP	mm-Wave	Multiple via-hole fabrication leads to complexity of the circuit
[20]	Silicon-On-Glass(SOG)	X-band	Only applicable for SOI wafer design.
[21]	Ceramic Package	5-6 GHz	Though the package was analyzed for K/Ka-band application, actual device was placed and measurement was taken for 5-6 GHz only.
Present Work	Standard Cavity type package	Ka-band	Simple structure, easy to fabricate, can be used for microwave frequencies up to Ka-band.

V. CONCLUSION

Standard cavity package, modified for RF-MEMS application has been analyzed in this work. Transmission line at 30 GHz is characterized after placing it into the package. Probable sources of loss mechanisms at Ka-band have been detailed here. Optimum number of bond-wires was found to eradicate extra complexity during packaging process. Package has been characterized for the frequency range of 29 to 31 GHz. The advantage of present work is the simplicity of the structure. A comparison of the current work with the literature is summarized in Table 6. Further, the performance of the package can be improved appreciably (reduction of insertion loss by 2 dB) after introducing a metallic plate like structure in the discontinuity zone inside the cavity (Structure 6 of Fig. 9). This process is under development.

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