Modeling, Design and Demonstration of Integrated Electromagnetic Shielding for Miniaturized RF SOP Glass Packages

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Abstract

This paper demonstrates, for the first time, an integrated trench-based shielding for electromagnetic interference (EMI) isolation between components in an ultra-miniaturized radio frequency (RF) package. A novel component-level shielding structure is explored and developed using metallized trenches formed in the build-up layers of ultra-thin glass substrates. Through full-wave electromagnetic (EM) simulation, the coupling between different passive structures are compared. Additionally, the shielding effectiveness of trench-based structures are compared with traditional via-based shields. Further, the shield effectiveness of different magnetic and non-magnetic shield materials are compared through analytical modeling. Based on these modeling results, a representative shield structure is designed, fabricated and characterized to correlate its performance with simulations. It is observed through measurements, that package-integrated trench-based shields provide up to 25dB more lateral isolation than via-arrays.

1. Introduction

Today's RF modules feature individually packaged actives and passives, assembled on a printed wiring board, as shown in Figure 1a. The increasing demand for multi-functional and portable devices on the other hand, drives the need for high-density integration of ultra-miniaturized components in multi-band RF sub-systems [1]. RF System-on-Package (SOP) modules with the 3D IPAC (Integrated Passives and actives) concept conceived by Georgia Tech – Packaging Research Center (GT-PRC) [2] enables simultaneous module miniaturization and performance enhancement by employing: a) an ultra-thin substrate; b) made of glass having very low electrical loss and exceptional dimensional stability; c) with double-side-assembled components separated by only about 50 µm in interconnect length using ultra-short through-package vias; d) embedded and surface-assembled ultra-thin actives and passives; and e) using ultra short interconnections with high current handling. This concept is illustrated in Figure 1b.

To realize such ultra-miniaturized RF modules using the 3D IPAC concept, advances in five key building blocks are essential: 1) ultra-thin low-noise high-gain actives, 2) thin-film low-loss RF and Power passives, 3) interconnections with least signal and power losses, 4) efficient thermal relief, and 5) high-density component integration with electromagnetic isolation. Advances in on-chip design drive continuous miniaturization and integration of actives [3]. Further, to facilitate passive component miniaturization, a number of low-loss thick-film and thin-film dielectrics are being developed for RF and power applications. [2, 4]. Low-temperature copper-copper thermo-compression bonding has enabled ultra-short low-parasitic interconnections at fine pitch [5]. Additionally, to provide thermal dissipation and isolation, package-integrated thermal relief approaches are being developed [6]. However, to address the increasing EM interference between components in ultra-miniaturized modules, there is a need to develop effective package-integrated EMI shields.

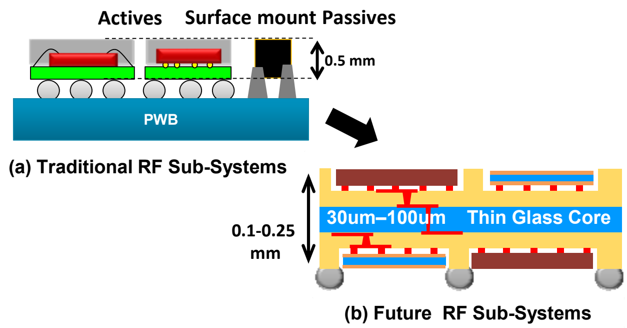

Figure 1. The new 3D IPAC approach for RF modules vs. traditional.

A number of methods are being employed to address the electromagnetic interference between components at different levels of a system hierarchy. Traditional EM shields were developed to comply with FCC regulations on radio frequency interference – to protect electrical systems from external EM interference and to prevent outward radiation from an equipment. In traditional modules, the components were packaged individually and assembled on a printed circuit board [5]. In such cases EM isolation between components was predominantly achieved through spatial isolation, and metallic cans were employed to shield one sub-module from another [6]. Since metallic cans were bulky and could also detune [7] the devices enclosed, conformal coating approaches were adopted [8]. Alternately, metallic shielding inside the over-mold have also been developed [9]. In addition, via-based shield approaches have been explored [10-13] to isolate components in a package or board. However, the higher component-density, enabled by the increasing miniaturization of components, necessitates the development of miniaturized and highly effective shielding techniques to address the increased EM interference between components in a single package.

In highly miniaturized RF modules, the distance of separation between components ranges from 0.1 - 3 mm. This signifies that, for frequencies at least up to 15 GHz, all the components lie in the near-field region (distance < $\lambda/2\pi$) of one another. Since the electric and magnetic fields are decoupled in the near field region and the magnetic fields have lower wave impedance, eliminating near-field magnetic interference between components is a challenge. Additionally, when providing EM isolation between components within a package, the thickness of the shield becomes a limiting factor to miniaturization. As shown in Figure 2 the effectiveness of an EMI shield reduces with decreasing shield thickness and with increasing proximity between components, Hence careful shield design and material selection is required for such component-level EMI shielding.

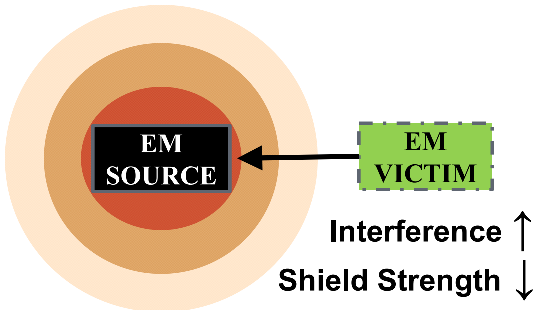

Figure 2. EM Shield effectiveness.

This paper demonstrates, for the first time, integrated trench-based shield structures that can be employed to mitigate EM interference between components in ultra-miniaturized RF SOP modules. This paper is divided into 7 sections. In Section 2, the EM simulations to study the coupling between package elements are discussed. The shield effectiveness of different materials are compared through analytical simulations in Section 3, followed by Section 4 where the performance comparison of different shield structures is discussed through full-wave EM simulations. In Section 5 and Section 6 the fabrication process of the proposed trench structures, their characterization and analysis are presented. The conclusions are presented in Section 7.

2. EM Coupling Between Package Elements

To understand the requirement of shielding, the lateral EM coupling between different package elements must be analyzed. The various package elements include passive components such as inductors and capacitors, and interconnections such as vias, transmission lines and chip bumps. The dimensions of these elements are dependent on the design rules of the particular package design. In this paper, the following package elements will be considered: 1) Through Package Vias (TPVs), 2) microstrip lines, 3) inductors, and 4) capacitors. The design rules of the package under consideration are tabulated below in Table I.

Table I: Table of Design Rules

Parameter	Dimension
Glass thickness, TPV diameter	100 µm, 60 µm
Metal thickness	8 µm
Dielectric thickness	15 µm

2a. Full-wave 3D EM Simulation Setup

In order to study the coupling between package elements, simulations were performed using HFSS – a full-wave 3D EM tool. The geometries and metal thicknesses of the different elements were constructed based on the design rules. To study the coupling between these elements, two of these elements were integrated into a simulation and the signal coupling was studied, assuming 400 microns of separation between the elements. The solution set-up type was “driven-terminal”, and lumped ports were employed to excite the structures as well as to study the induced interference. The top view of the typical simulation set-up consisting of a TPV, a capacitor, an inductor and a transmission line (TL) is shown in Figure 3.

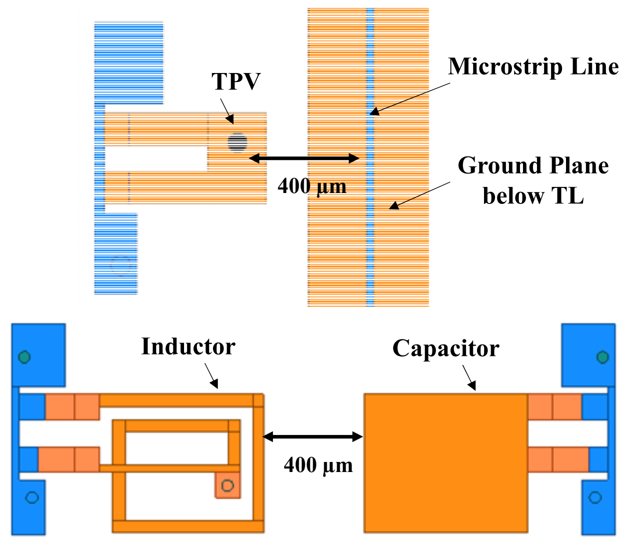

Figure 3. Top view of the typical simulation setup.

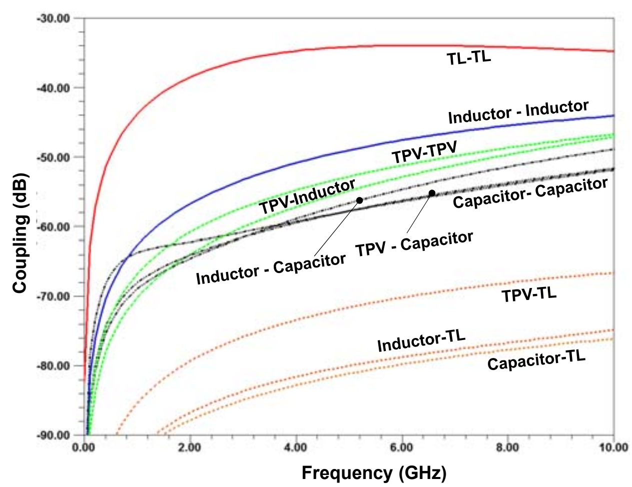

Figure 4. EM coupling between package elements.

2b. Simulation results and analysis

The lateral coupling between different elements are compared in Figure 4. It can be observed that the coupling is highest between transmission lines with common ground plane. The next highest coupling is between inductors as they do not have a tightly coupled ground reference. Further, since inductors and TPVs are current-based elements, the coupling onto an inductor from a TPV was observed to be higher than that from a capacitor, which is a voltage-based structure. Further, since microstrip transmission lines are tightly coupled to a ground plane, it was observed that the coupling was the least between other elements and a microstrip line.

Hence, transmission lines are the least susceptible to lateral EM interference from other package elements, and radiate the least as well.

3. Shielding effectiveness of materials

The effectiveness of a shield is dependent on the shield material, its distance from the radiation source, and its geometry. This section illustrates the impact of material properties on shielding effectiveness. The effects of shield geometry and apertures on the shield effectiveness were ignored. Analytical expression for the shield effectiveness of materials and material stacks are employed to compare the shield effectiveness of different materials for the required application [14, 15].

3a. Analytical simulation setup and assumptions

Substrate-compatible metals such as copper, nickel, and aluminum were considered for this analysis, along with nickel-iron (NiFe) and cobalt-zirconium (CoZr). The properties of NiFe and CoZr measured by [16-18] are considered as guidelines. The different material properties are summarized in Table II. Magnetic materials lose their magnetic properties (permeability becomes unity) beyond a certain frequency that is specific to each material. This frequency is known as the ferro-magnetic resonance (FMR) frequency. Above its FMR frequency, a magnetic material absorbs the radiation incident on it. The absorption due to ferromagnetic resonance needs to be determined through experimental characterization.

Table II: List of Material Properties

Material	Resistivity (µ ohm cm)	Permeability	FMR
Copper	1.68	1	-
Aluminum	2.8	1	-
Nickel	6.99	100	20MHz
CoZr	100	200	3 GHz
NiFe	50	400	1 GHz

Analytical calculations (without FMR effects) were performed to estimate the shield effectiveness of the materials, assuming a distance between source and shield of 0.5mm – the typical separation between components in a miniaturized sub-system. The simulation considers 0.5GHz - 20GHz since this covers the operating frequencies of WLAN and cellular RF modules, including three harmonics. The impact of thickness on shield effectiveness is also studied by varying the metal thickness from 1 µm up to 5 µm.

3b. Comparison of materials and thicknesses

The comparison of shield effectiveness between the different materials is shown in Figure 5. It can be observed that copper has the best shield effectiveness because of its low resistivity, followed by aluminum. Nickel and nickel-iron show low shield effectiveness since the frequency range under consideration is are already past their FMR. However, for cobalt zirconium, since the FMR occurs only at 3GHz, it can be seen that till 3GHz its shield effectiveness is as good as that of aluminum. This effect of reduced permeability beyond FMR can be observed in Figure 5. Since shielding due to FMR is not captured in this analytical model, the actual shielding effectiveness can be expected to be higher for Ni, NiFe and CoZr. The effect of metal thickness on shield effectiveness for copper is depicted in Figure 6. It can be seen that the shield effectiveness increases with increasing metal thickness since the dominant shielding phenomenon at these frequencies is absorption loss which depends on the thickness of the shield metal.

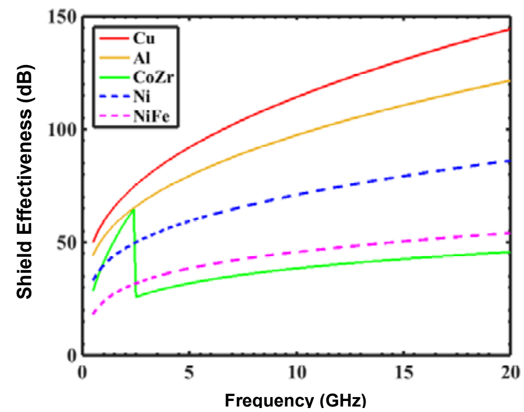

Figure 5. Comparison of shielding effectiveness of different materials.

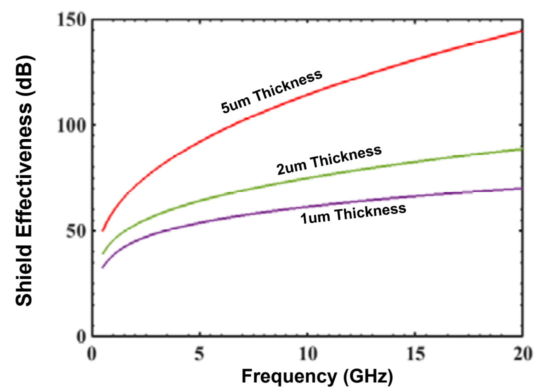

Figure 6. Shield effectiveness with varying thickness of the shield metal.

4. Shielding Effectiveness of structures

The type of structure that is employed for shielding is an important consideration in shield design. It is also important that the structure is compatible with the fabrication process for easy integration with the rest of the sub-system. In this regard, two types of structures were identified – vias and trenches. The shielding effectiveness of via array is compared with that of trenches, in a multi-layer package substrate through full-wave EM simulations. Further, since the coupling between transmission lines was observed to be the highest among all package elements, transmission lines were used to study the effectiveness of the different shield structures.

4a. Design rules for via and trenches, Metal thicknesses

The design rules of the substrate under consideration are tabulated in Table III.

Table III: Design Rules for the shield structure.

Parameter	Dimension
Micro-Via diameter, Trench diameter	45 µm
Metal thickness	6 µm
Dielectric thickness	15 µm

4b. Full-wave 3D EM Simulation setup

The simulations to study the shield effectiveness of structures were performed using Sonnet– a full-wave EM simulator. The geometries and metal thicknesses of the different elements were constructed based on the design rules mentioned in Table III. To study the shield effectiveness, a pair of microstrip transmission lines of length 15mm, separated by 180 microns, were considered and the required shield structure was integrated between them. The far-end crosstalk between these lines was employed to compare the shield effectiveness of the shield structures. The set-up is depicted in Figure 7, where each transmission line is terminated with 50-ohms on one end and probed at the other.

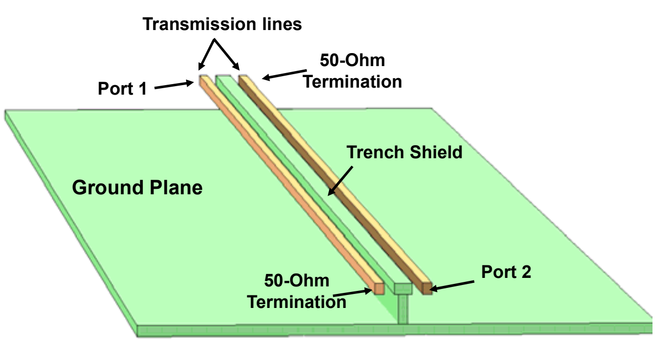

Figure 7. Simulation set-up showing transmission lines separated by a trench-based shield.

4c. Comparison of structures

The simulations of the via array and trench were performed and the comparison of their shield effectiveness is shown in Figure 8. The shield effectiveness of the trench structure was more than that of the via array, with the highest simulated EM isolation between the transmission lines being 20dB for the trench and 25dB for the via array.

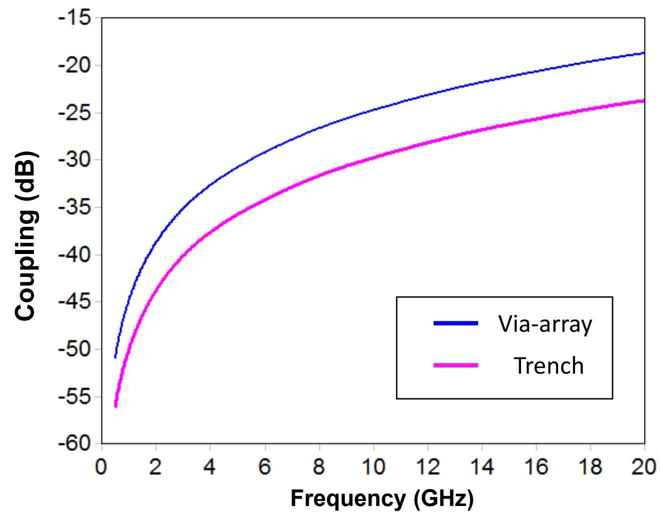

Figure 8. Comparison of TL-TL coupling in presence of via-arrays and trenches.

5. Fabrication

The transmission lines were designed as per the simulation set-up and fabricated on glass substrates. The advantage of the proposed trench structure is its ability to be integrated into standard substrate fabrication processes [19]. Patterning and metallization of the core metal layers and the through package vias were performed using double-side wet metallization techniques. Following this, the build-up polymer was laminated on both sides of the substrate. The shielding trenches and the micro vias were simultaneously formed on the build-up through laser ablation using ultraviolet laser. The metallization of the trenches was carried out along with the metallization of the micro via and the build-up metal pattern. An image of the fabricated structures is shown in Figure 9.

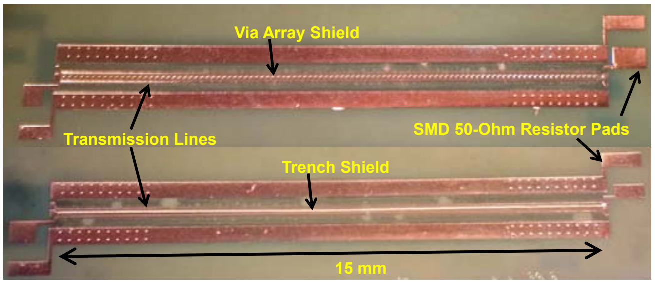

Figure 9. Transmission lines with Via-array and trench shield, fabricated on ultra-thin glass substrate.

6. Characterization

After the substrate fabrication, 50-Ohm SMD resistors were assembled on the coupons to terminate the lines. Following this, RF characterization using GSG RF probes was carried out using a vector network analyzer. To measure the EM interference between the lines, two-port S-parameter characterization was performed. The measurements showed reasonable correlation with the simulations, with the trench structures offering up to 20dB increased isolation between components, compared to via-array shields.

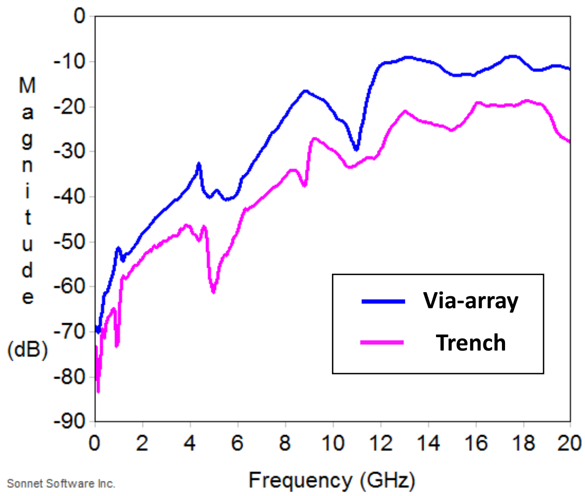

Figure 10. Comparison of measured TL-TL coupling in presence of via-arrays and trenches.

7. Conclusions

A novel trench-based EM shielding approach that offers a low-cost, substrate-integrated solution for component-level shielding inside a package is presented. Analytical modeling was employed to determine the shield effectiveness of different materials. Comparison of EM coupling between various package elements was also performed to determine their susceptibility to EM interference. To the best of the authors' knowledge, this is the first paper to introduce and demonstrate an integrated trench-based EM shielding between components for ultra-thin glass RF packages.

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