Lumped Resonances and The Corresponding Noise Coupling Mechanism in Flex PCBs

Songping Wu[#1], Sungnam Kim[*2], Jea Su Park[*3], Inho Choi[*4], and Jun Fan[#5]

[#]*UMR/MST EMC Laboratory, Missouri University of Science and Technology (formerly University of Missouri-Rolla), Rolla, MO 65409, USA*

[1]swhv7@mst.edu, [5]jfan@mst.edu

* *LG Electronics, 19-1, Cheongho-ri, Jinwi-myeon, Pyeongtaek-si, Gyeonggi-do, 451-713, Korea*

[2]snamee77@lge.com, [3]jaesupark@lge.com, [4]ihchoi04@lge.com

***Abstract*— A flex PCB design with multiple traces and a discontinuous ground plane demonstrates multiple resonances in its insertion loss at the frequencies lower than 1 GHz. This paper investigates the root cause of these resonances. An equivalent circuit based on a multi-conductor transmission-line approach is developed, and the noise coupling mechanism is studied using this equivalent circuit. The resonances are found to be caused by the mutual inductances among the traces in the region without the ground plane and the self capacitances of the neighbouring open-ended traces.**

Key words: Flex PCB, lumped resonances, noise coupling mechanism, equivalent circuit model.

I. Introduction

Flexible printed circuit boards (Flex PCBs) are commonly used for data transmissions between printed circuit boards wherever maneuverable and bendable connections are required, such as in cell phones or laptops. The flexibility of the flex PCBs is achieved by producing a bundle of thin traces above thin layers of dielectric materials [1].

The Flex PCB structure investigated in this paper is shown in Fig.1. It has 28 signal traces and 2 ground traces. These traces are buried microstrip structures with a thin dielectric layer on top of them. The bottom layer has solid ground planes in the fan-out regions at the two ends of the flex PCB. In the middle narrow region, there's no ground plane. In other words, the ground plane in the bottom layer is not continuous. This design feature is necessary for the flex PCB to be able to bend easily when needed.

In the Flex PCB assembly, the trace routings are dense and the signal return ground is not continuous. These lead to strong noise coupling among the conductors. They can also result in noise radiation. In other words, a significant amount of noise may be coupled to the other portion of the system, such as an RF antenna. This noise can then result in degraded RF performance, or even system malfunction.

A particular issue in this Flex PCB design is the existence of resonances in its insertion loss. The measured result shown in Fig. 2 is the channel response of signal trace #1 in the Flex PCB structure. The measurement was performed using a vector network analyzer and a probe station. Except signal trace #1, the other signal traces are open-ended. Multiple resonances are observed at the frequencies from 200MHz to 1GHz, which are within the working frequency range of certain cell phones. The resonances at these frequencies can cause significant signal integrity breakdown.

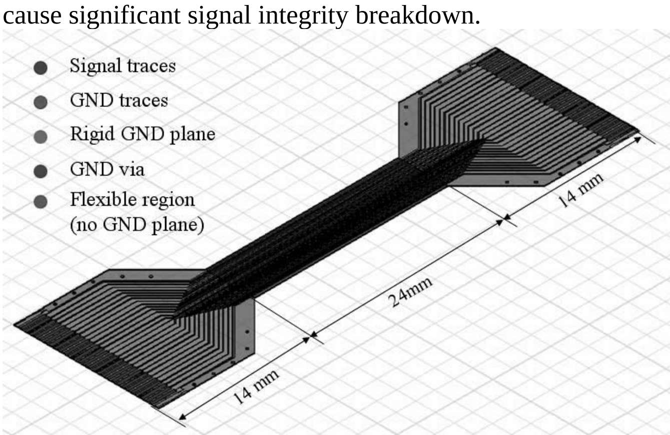

Fig. 1 The Flex PCB structure under study

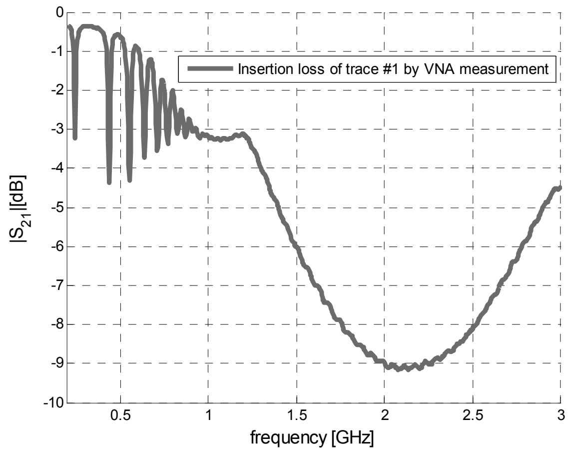

Fig. 2 Measured $|S_{21}|$ of signal trace #1

At these resonant frequencies, the Flex PCB structure is still electrically small. In other words, the resonances below 1 GHz cannot be the distributed resonances caused by wave reflections. Rather, they must be lumped ones resulting from the parasitics of the Flex PCB structure.

In order to study the root cause of these lumped resonances, a multi-conductor transmission-line approach is used to extract the parasitic inductances and capacitances. The corresponding equivalent circuit is developed in Section II.

Section III describes the noise coupling mechanism that results in the lumped resonances, followed by the conclusions in Section IV.

II. Development of the Equivalent Circuit

A. Geometry Simplification

To focus on the root cause of the lumped resonances, a simplified geometry is adopted in the following study as shown in Fig.3. Only two signal traces plus one ground trace are considered in the simplified geometry. In addition, all the trace bending and cross-sectional variations in the original Flex PCB design are neglected. In other words, all these three traces are straight lines with uniform cross sections. There's a solid ground plane in Parts I and III in the bottom layer. In Part II, no ground plane exists in the bottom layer.

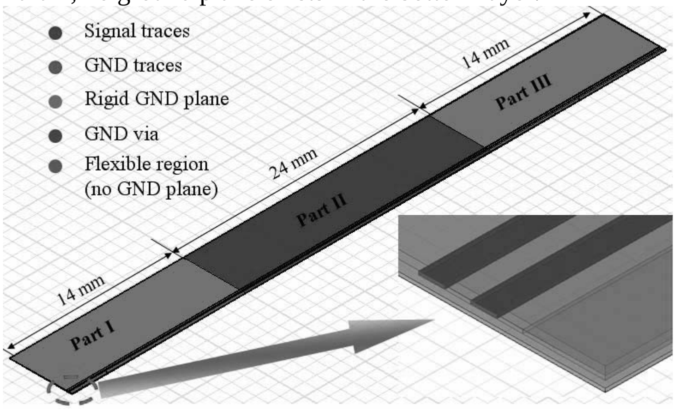

Fig. 3 A simplified Flex PCB structure

The simplified geometry produces one lumped resonance at approximately 1 GHz, as shown in Fig. 4, where the insertion loss of signal trace #1 (the trace right next to the ground trace) simulated from HFSS, a full-wave modeling tool, is illustrated. Signal trace #2 is open-ended at both ends in the simulation.

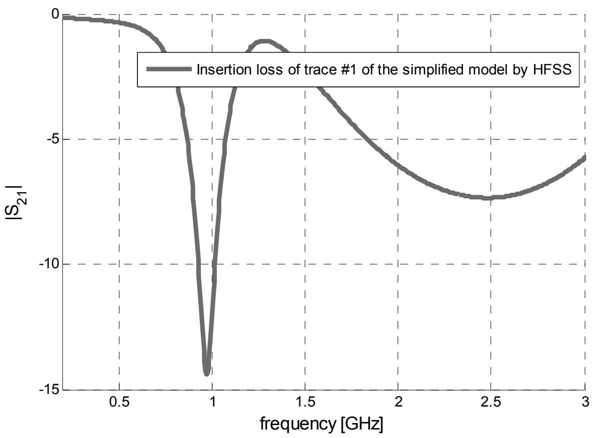

Fig. 4 Simulated $|S_{21}|$ of signal trace #1 in the simplified Flex PCB structure

B. Lossless Lumped Equivalent Circuit Model

As mentioned earlier, the Flex PCB structure is electrically small at the lumped resonant frequencies. The same is true for the simplified Flex PCB structure. As shown in Fig. 3, the longest segment (Part II) is 24mm. At 1 GHz, 24 mm is smaller than one sixth of the wavelength. Thus it is reasonable to use the lumped RLGC components to study these lumped resonances. In addition, since the resonant frequency instead of the magnitude is of interest here for the root cause, only inductance and capacitance terms are considered. The lossy terms, i.e., R and G, which relate to the resonant magnitudes, are neglected in the following discussions.

Fig. 5 illustrates the lumped equivalent circuit model. Each trace segment (Part I, II, or III) is modeled as a π-circuit with shunt capacitances and series inductances representing the parasitic self capacitances and inductances, respectively. Specifically, C1, C2, C3, C4, L1, L2 and L3 model signal trace #1. Similarly, C5 to C8 and L4 to L6 model signal trace #2. The coupling of the traces is modeled as the mutual capacitances and the mutual inductances. All the component values are extracted using Ansoft Q2D, a 2D cross-sectional analysis tool. The cross section of each segment is simulated to obtain the per-unit-length parameters of a multi-conductor transmission line, and then these per-unit-length parameters are multiplied with the length of each segment to obtain the values of the lumped circuit components used in Fig. 5.

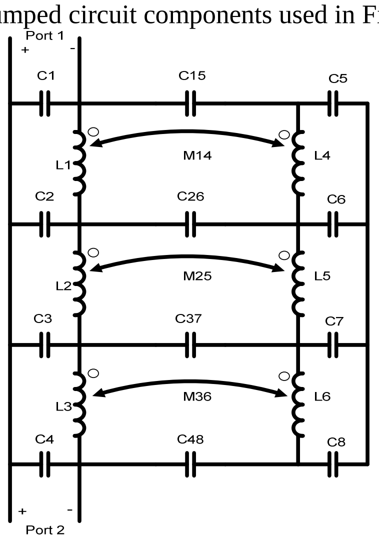

Fig. 5 A lumped equivalent circuit model for the simplified Flex PCB structure

Fig. 6 shows the simulated insertion loss result of the signal trace #1 using the lumped circuit model shown in Fig. 5. Again, signal trace #2 is open-ended at both ends. From Fig. 6, it is clearly seen that the 1GHz lumped resonance is well modeled by the lumped equivalent circuit model. Interestingly, there are two other resonances at the frequencies higher than 1.5 GHz. However, these two resonances are not physically meaningful anymore, since the geometry is no longer electrically small at those frequencies, and thus the lumped equivalent circuit model shown in Fig. 5 is no longer valid.

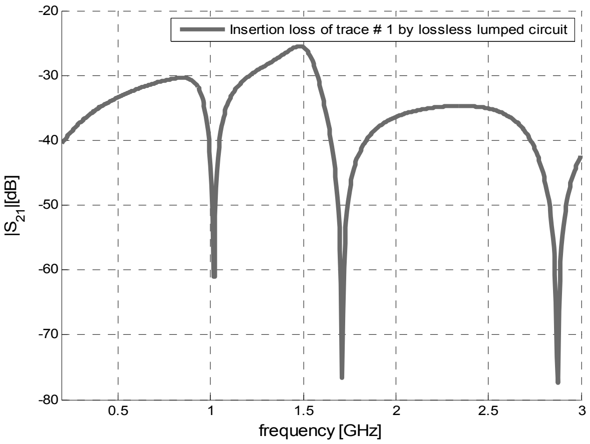

Fig. 6 Simulated $|S_{21}|$ of signal trace #1 using the lumped equivalent circuit model shown in Fig. 5

III. NOISE COUPLING MECHANISM OF THE LUMPED RESONANCES

The lumped equivalent circuit model discussed in Section II accurately describes the lumped resonance at approximately 1 GHz. In order to further find out what kind of noise coupling mechanism, in other words, what circuit components, directly cause the resonance, some additional discussions are needed.

A. Noise Coupling Mechanism

By further simplifying the lumped equivalent circuit model shown in Fig. 5, one could identify the dominant circuit components that contribute to the lumped resonance. In other words, only a few components in the lumped circuit model are kept and the rest is discarded. Through a few trial-and-errors, it is found that the mutual inductance between the two signal traces in the Part II region and the self capacitances of signal trace #2 together contribute to the lumped LC resonance at 1 GHz. Fig..7 shows the further simplified lumped equivalent circuit model, keeping only the mutual inductance M25 and the self capacitances C5-C8 of signal trace #2. All the self capacitance terms and self inductance terms of signal trace #1 are omitted, as well as all the self inductance terms of signal trace #2. In addition, all the mutual capacitance terms between two traces and the mutual inductance terms between the two traces in Parts I and III are eliminated, too.

The simulated insertion loss of signal trace #1 using the further simplified lumped equivalent circuit model is shown in Fig. 8, where signal trace #2 is open-ended at both ends. The lumped resonance appears again at the frequency of approximately 1GHz. In other words, this lumped resonance is demonstrated to be caused by the mutual inductance between the two signal traces in the Part II region where no ground plane exists together with the self capacitances of signal trace #2.

This result can be explained from the geometry itself too. For the Part I and Part III of the Flex PCB in Fig.3, since there is a big continuous ground plane beneath the traces, most of the field is between each trace and the ground plane, and noise coupling between the two traces is small. For the Part II of the Flex PCB, there is no large solid ground plane under the signal conductors. The field strength between the two signal traces in this region increases significantly, resulting in a larger noise coupling between the traces.

Another observation is that inductive coupling dominates over capacitive coupling between the traces at the frequencies lower than 1 GHz. Because in the Part II region of the Flex PCB structure the return path through a ground plane is not available, the inductively coupled currents are much larger than the capacitively coupled currents. In this regime, the noise behavior is dominated by inductive coupling. If Part II had a solid ground plane, capacitively and inductively coupled currents would be in the same order [2].

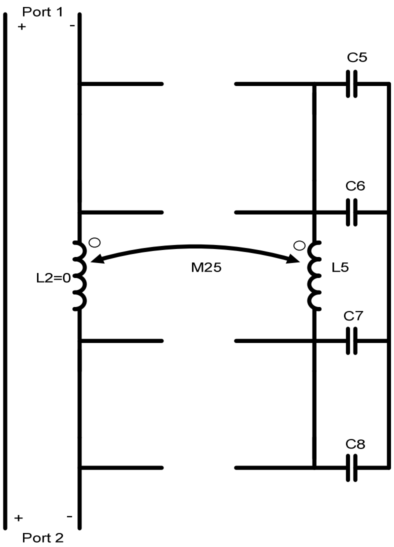

Fig. 7 A further simplified lumped equivalent circuit model for the Flex PCB structure shown in Fig. 3

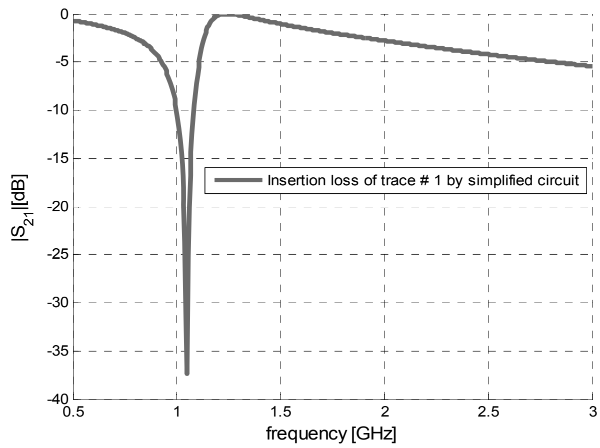

Fig. 8 Simulated $|S_{21}|$ of signal trace #1 using the further simplified lumped circuit model shown in Fig. 7

B. Further Validation

In order to validate the conclusion drawn from the previous study, another open-ended signal trace is added next to signal trace #2 in the simplified Flex PCB structure shown in Fig. 3. Since there are two open-ended traces coupled to signal trace #1 in this case, correspondingly two lumped resonances appear as illustrated in the HFSS full wave simulations as shown in Fig. 9. Two resonances at approximately 0.7 GHz and 1.4 GHz are shown in the insertion loss of signal trace #1. Assuming that the lumped resonances are mainly contributed by the mutual inductances among the signal traces in the Part II region and the self capacitances of signal traces #2 and #3, the simplified lumped equivalent circuit model is established in Fig. 10.

The simulated insertion loss of signal trace #1 using the simplified lumped equivalent circuit model shown in Fig. 10 is also shown in Fig. 9. As it can be clearly seen, the lumped circuit model predicts the two lumped resonances pretty well compared to the HFSS results. In other words, this result validates the conclusion that the lumped resonances are due to the mutual inductances in the region without the ground plane, as well as the self capacitances of the open-ended traces.

The more signal traces, the more lumped resonances. Therefore, for the real Flex PCB structure shown in Fig, 1 with 28 signal traces, there are multiple lumped resonances, as illustrated in Fig. 2.

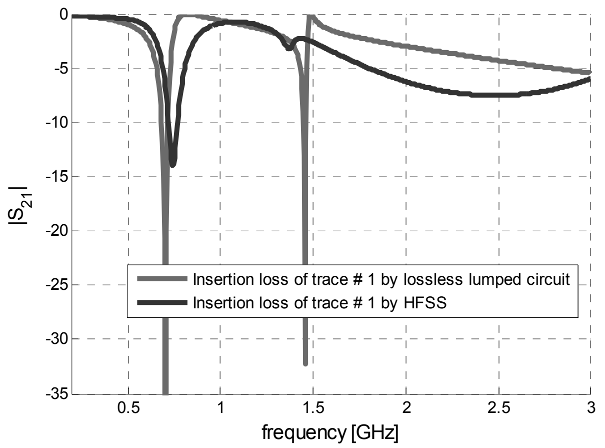

Fig. 9 Simulated $|S_{21}|$ of signal trace #1 with totally 3 signal traces

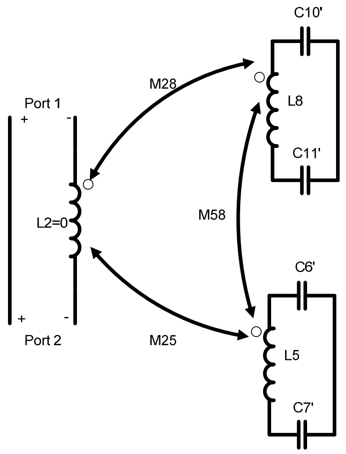

Fig. 10 A simplified lumped equivalent circuit model for the 3-trace Flex PCB

IV. CONCLUSION

The lumped resonances in Flex PCBs are mainly caused by the mutual inductances among the traces in the region without the ground plane where inductive coupling is strong, together with the self capacitances of the open-ended signal traces.

Since the resonances are lumped, a simple lumped equivalent circuit model, obtained from a multi-conductor transmission-line approach, can be used to study the root cause of these resonances. The equivalent circuit model has demonstrated to be an effective approach to identify the major noise coupling mechanism.

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