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TECHNOLOGIES TO IMPROVE HIGH FREQUENCY CHARACTERISTICS OF INTEGRATED EMI FILTERS

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***Abstract* – One of the major goals in designing of the integrated EMI filters is to improve their high-frequency characteristics. To achieve this, special technologies need to be developed, including the mechanisms for suppression of the equivalent parallel capacitance (EPC) and of the equivalent series inductance (ESL), in spite of increasing the high-frequency losses. In this light, the paper studies the technologies used to reduce the Equivalent Series Inductance (ESL) for EMI filters integration. The ESL of integrated L-C with three different connection methods are proposed, namely: the L-C series connection method, the two-point capacitance connection method and the four-point transmission line connection method, as they are described below. Final conclusions will end the paper.**

Keywords: *equivalent series inductances, L-C structure, passive integration, EMI filter, insertion loss simulation..*

1. INTRODUCTION

The main component of an EMI filter is the low pass filter; therefore, in order to develop the integrated low pass filter, the integrated L-C structure must be carefully studied and modelled.

The planar integrated L-C structure consists of alternating layers of conductors, dielectrics, insulation and ferrite materials that produce an integrated structure with similar terminal characteristics as the lumped components. The exploded view of an integrated L-C structure was shown in Figure 1.

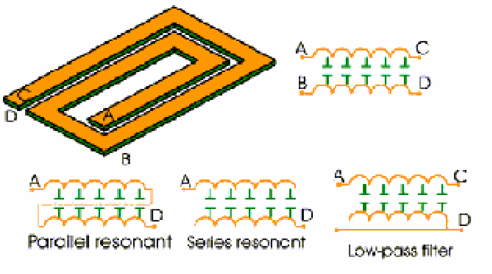


Figure 1: The integrated L-C structure.

The integrated L-C winding consists of a dielectric substrate with conductor windings directly deposited on both sides, thus resulting in a structure having both sufficient inductance and capacitance. This realizes the equivalent integrated capacitance as well as the inductance. By appropriately terminating the four terminals A, B, C and D of the integrated L-C winding, the same structure could be configured as equivalent L-C series resonator, parallel resonator or low pass filter. To integrate the EMI filter, the L-C low pass filter configuration is used, where AD is the input port and CD is the output.

The existing integrated LC technologies and design methodologies were mostly developed for high-frequency power passive components integration in order to achieve high efficiency and high power density. Since functions and requirements are different for passive components in EMI filters, special technologies need to be developed for EMI filter integration.

The magnetic energy stored in a capacitor and its associated interconnection trace loops can be represented by the equivalent series inductance (ESL). The ESL of a capacitor normally consists of the self-inductance, the lead inductance, and the interconnection loop inductance. Figure 2 shows a typical connection of a discrete filter capacitor, in which L_1 represents the self inductance of the capacitor, L_2 represents the lead and interconnection inductance, and L_3 and L_4 represent the input and output trace loop inductance, respectively. In practice, the magnetic coupling between the input and output trace loops cannot be ignored. Assuming the mutual inductance is M, L_3 and L_4 can be decoupled by applying the decoupled T equivalent circuit, as shown in Figure 3.

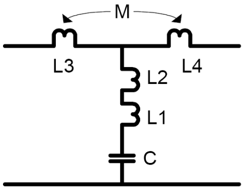


Figure 2: Capacitor's ESL.

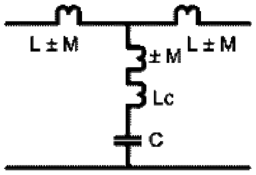


Figure 3: Decoupling equivalent circuit.

Considering the magnetic coupling of L_3 and L_4, the equivalent series inductance of the capacitor is given by:

$$L_e = L_c \pm M \qquad (1)$$

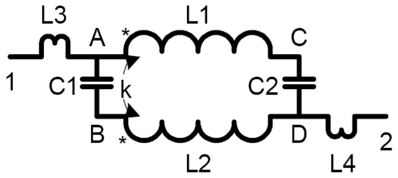
where $M = k \cdot \sqrt{L_3 L_4}$ and k is the coupling coefficient. The plus or minus signs are determined by the coupling direction.

The conventional solution to minimize ESL is always focused on minimizing the lead and interconnection trace length, the input and output loop inductance, and the magnetic coupling among them. Another method of utilizing the mutual inductance to cancel ESL is achieved by changing the coupling direction of the input and output loops and tuning the loop inductances. When the two loops are reversely coupled and M is equal to Lc, ESL can be completely cancelled. This method has been applied to discrete low-pass filters and promising results have been shown [3]. However, in reality, because the magnetic flux generated by the interconnection loops is a complicated 3D structure, and it is closely related to the layout and the nearby components and circuits, no appropriate model is available. Even 3D finite element simulation will not be adequate. The design is almost based on “trial and error” and a good cancellation effect is difficult to achieve.

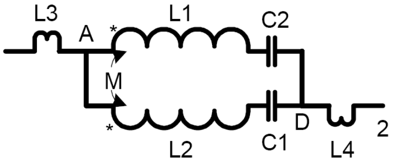
For integrated EMI filters, the equivalent capacitor is implemented by the distributed capacitance of the integrated L-C winding. To reduce ESL, the self-inductance and interconnection inductance have to be reduced or shifted. The integrated L-C is a four terminal network. Different connection types of this four-terminal network will give a different ESL of the equivalent capacitor. The ESL of integrated L-C with 3 different connection methods is studied, as described below.

2. L-C SERIES CONNECTION

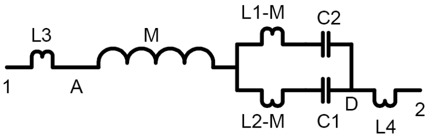
Figure 4-(a) shows the simplified equivalent circuit of an integrated LC winding connected as a LC series resonator, where L_1 and L_2 are the self-inductance of the top and bottom conductor, respectively. Normally they have the same value L; M is the mutual inductance of L_1 and L_2; L_3 and L_4 are the lead inductance. The distributed capacitance is represented by two lumped capacitors C_1 and C_2, each is half of the equivalent capacitance C. All the losses are overlooked at this time to simplify the analysis.



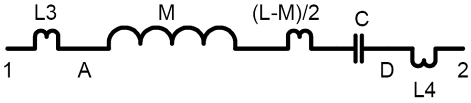
(a) original equivalent circuit.



(b) C_1 and L_2 exchange position.



(c) decouple T-equivalent circuit.



(d) simplified equivalent circuit.

Figure 4: Derivation of ESL of L-C series connection.

After the circuit transformations shown in Figure 4-(b) through Figure 4-(d), it is evident that the ESL of the equivalent capacitance is equal to:

$$ESL = M + \frac{(L-M)}{2} + L_3 + L_4 \qquad (2)$$

Normally the top and bottom conductor windings are closely coupled, $M \approx L$. The self inductance of the winding is much larger than the leakage and the interconnection inductance. Therefore, in this case, ESL is approximately equal to L.

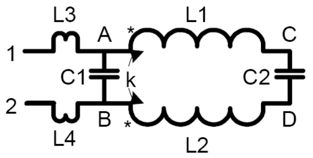
3. TWO-POINT CAPACITANCE CONNECTION

Another method of connecting integrated L-C windings as a capacitor is the normal two-point connection method, shown in Figure 5-(a), where A and B are the two terminals of the integrated L-C winding.

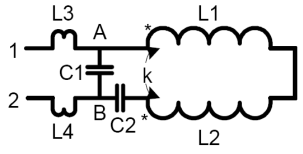
In this case, as shown in the circuit transformations shown in Figure 5-(b) to Figure 5-(d), the ESL is given by:

$$ESL = L_3 + L_4 + L_s \tag{3}$$

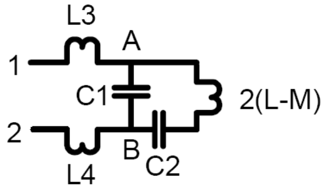
where $L_s = L - M$ is the leakage inductance. It is evident that the ESL is much smaller than the previous case since it is only the sum of the interconnection and leakage inductance.



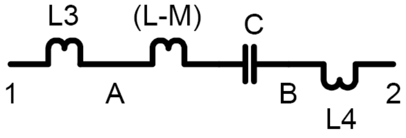
(a) original equivalent circuit.



(b) C_2 and L_2 exchange position



(c) decoupled circuit.



(d) simplified equivalent circuit.

Figure 5: Derivation of ESL of two-point capacitor connection.

In the previous two cases, the interconnection inductance is always in series with the equivalent capacitor. It lowers the self-resonant frequency of the capacitor and reduces the high-frequency attenuation. To solve this problem, the four-point transmission line connection method is proposed.

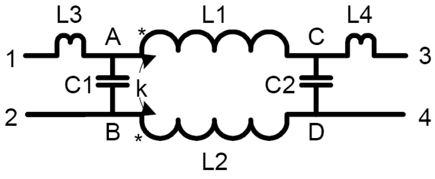
4. FOUR-POINT TRANSMISSION LINE CONNECTION

In this case, as shown in Figure 6-(a), the integrated L-C winding is connected as a transmission line, where its four terminals A, B, C and D are all utilized. By using the circuit network theory, the four-terminal network shown in Figure 6-(a) can be represented by its Z-parameter T-equivalent circuit, shown in Fig. 6-(b), where Z_1, Z_2 and Z_3 are given by:

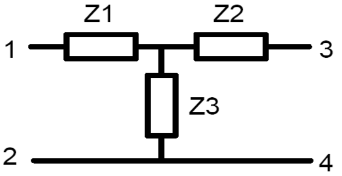
$$Z_1 = j\omega L_3 + \frac{j\omega L_s}{1-\omega^2 \frac{L_s C}{2}} \tag{4}$$

$$Z_2 = j\omega L_4 + \frac{j\omega L_s}{1-\omega^2 \frac{L_s C}{2}} \tag{5}$$

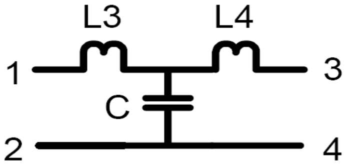
$$Z_3 = \frac{1}{j\omega C} \cdot \frac{1}{1-\omega^2 \frac{L_s C}{2}} \tag{6}$$



(a) original equivalent circuit.



(b) T equivalent circuit.



(c) simplified circuit.

Figure 6: Equivalent circuits of 4-point transmission line connection.

Usually the leakage inductance is very small. The equivalent circuit can be simplified to Figure 6-(c). It is interesting to see that the lead and interconnection inductance has been moved out of the capacitor branch. It implies that the ESL for this case is only the self inductance of the capacitor. Hence, its high frequency characteristics are improved.

5. INSERTION LOSS SIMULATION

To evaluate the above connection methods, the insertion losses of the integrated L-C winding under these configurations are simulated by using PSpice. The schematic is shown in Figure 7. The component parameters are given in the schematic as well and they are typical values of a practical circuit.

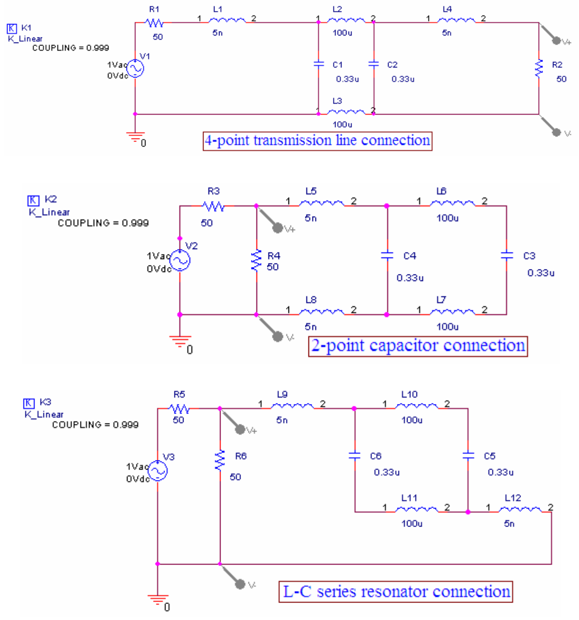


Figure 7: Schematic of insertion loss simulation.

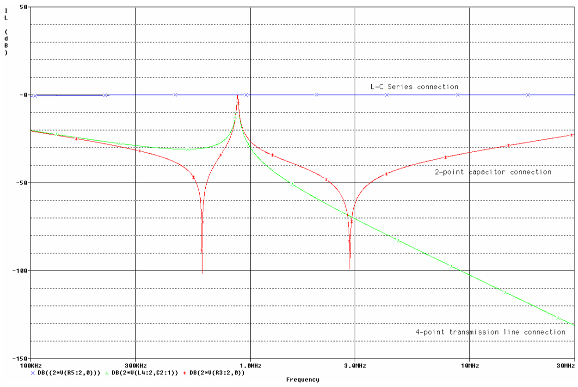


Figure 8: Simulated insertion losses comparison.

The simulated insertion losses are shown in Figure 8. It is shown that the integrated L-C with a four-terminal transmission line connection has much better high frequency characteristics. It is also evident that the most-often used L-C series connection method for other power passive components integration cannot be used at all because of the high ESL.

6. CONCLUSION

The three methods outlined in the paper are able to reduce the equivalent series inductance (ESL) for EMI filter integration and to improve high frequency characteristics of integrated EMI filters.

References

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