An ESL-cancelling circuit for a film capacitor using vertically stacked coupled square loops

Satoshi YONEDA[†a)], ***Member***, **Akihito KOBAYASHI**[†], ***non-Member***, **Norihiko AKASHI**, ***Member***, ***and*** **Eiji TANIGUCHI**[†], ***Member***

An ESL-cancelling circuit for a film capacitor using vertically stacked coupled square loops is reported in this paper. The circuit is applicable for shunt-connected capacitors whose equivalent series inductance (ESL) causes deterioration of filter performance at frequencies above the self-resonant frequency. Two pairs of magnetically coupled vertically stacked loops are used in the circuit those can equivalently generate negative inductance in the shunt path to cancel the ESL and improve filter performance. The ESL-cancelling circuit for a 1-µF film capacitor was designed according to Biot-Savart law and EM-analysis, then was fabricated with an FR4 substrate. The measured result showed that filter performance was improved by more than 20-dB at the frequencies above the self-resonant frequency. S_{dd21} less than -40 dB at 1 MHz to 100 MHz was also achieved which is, in principle, difficult to realize with any kind of single bulky shunt-connected capacitor.
keywords: *EMC, Equivalent series inductance* (*ESL*)*, Filter. Film capacitor.*

1. Introduction

A shunt connected capacitor have been normally and widely used as a filter circuit in a broad range of electronic devices. Figure 1 shows a simplified configuration of a shunt-connected capacitor which simply consists of a capacitance connected in shunt between a differential pair. However, in practical, two parasitic components, equivalent series inductance (ESL) and equivalent series resistance (ESR), are added shown as L_{ESL} and R_{ESR} in the figure. Although the filter works well as intended at frequencies below the self-resonant frequency of the shunt path, on the other hand, filter performance is deteriorated at frequencies above the self-resonant frequency where L_{ESL} becomes dominant. This problem is unavoidable in principle due to physical size of capacitors, and particularly can be exacerbated when a bulky film capacitor is required for its high voltage durability.

Recently, various configurations have been reported those can improve the deterioration caused by ESL [1]-[4]. In the configurations, magnetic coupling is utilized to add negative inductance to the shunt path, which can reduce, or sometimes cancel, ESL of the shunt path and improve the deterioration of filter performance as illustrated in Fig. 2. Note that when ESL is completely cancelled to be zero, the lowest value of filter performance merely depends on ESR.

In this paper, an ESL-cancelling circuit using vertically stacked coupled square loops is proposed and a prototype evaluation result for a 1-µF film capacitor is presented. At first, frequency characteristic of a filter circuit which simply consists of a 1-µF film capacitor connected between a differential pair is measured, and the measured result showed that self-resonant frequency is 1 MHz, and that filter performance is deteriorated at frequencies above 1 MHz. Considering this circuit as a reference circuit, an ESL-cancelling circuit using vertically stacked coupled square loops is designed according to Biot-Savart law and EM-analysis. The designed result showed that the square loops with a side of 12 mm can improve filter performance by more than 20 dB at frequencies above the self-resonant frequency. Finally, a prototype configuration is fabricated, and the measured result showed good agreement with the designed result, which demonstrates the effectiveness of the proposed circuit.

2. Configuration

Figure 3 shows a configuration of an ESL-cancelling circuit for a film capacitor using vertically stacked coupled square loops, and Fig. 4 shows conductor patterns on the dielectric substrate in Fig. 3. A film capacitor is connected

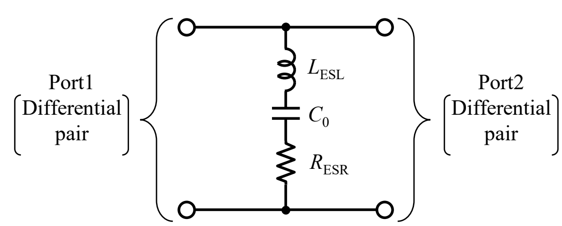


Fig. 1 A simplified configuration of a shunt-connected capacitor.

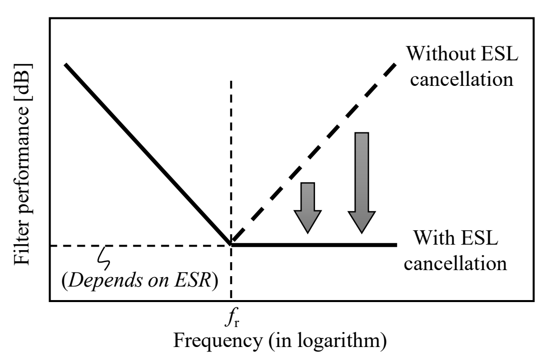


Fig. 2 Improvement of filter performance by an ESL cancellation.

[†]The authors are with Mitsubishi Electric Corporation, Information Technology R&D Center, Kamakura city
[a)] E-mail: Yoneda.Satoshi@aj.Mitsubishielectric.co.jp

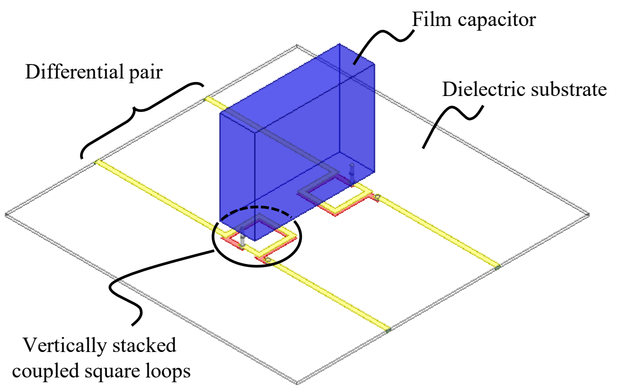
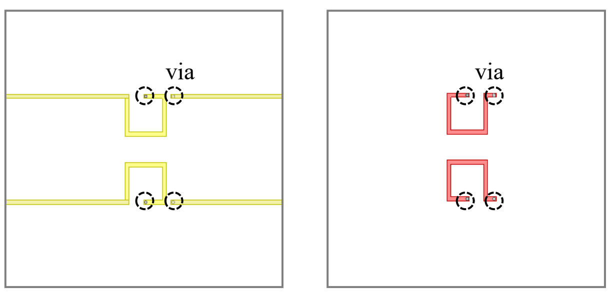


Fig. 3 A configuration of an ESL-cancelling circuit for a film capacitor using vertically stacked coupled square loops.



(a) Top view (b) Bottom view (transparent)

Fig. 4 Conductor patterns on the dielectric substrate in Fig. 3.

in shunt between a differential pair, and square loops on the upper and the bottom surface of the substrate are connected before and after the shunt connection point to configure vertically stacked coupled square loops. Figure 5 shows the equivalent circuit of this configuration, where the shunt path is represented by an RLC series circuit (R: R_{ESR}, L: L_{ESL}, C: C_0), and two pairs of vertically stacked coupled square loops are represented by inductors magnetically coupled and connected before and after the shunt connection points (self-inductance: L_0, mutual inductance: M_0).

In general, magnetic coupling shown by dots in Fig. 5 is known to be equivalent to a transformation that adds a positive inductance ($+M_0$) to the self-inductance and a negative inductance ($-M_0$) to the shunt path. By applying this transformation to the circuit shown in Fig. 5, equivalent circuit can be obtained where negative inductance ($-2M_0$) exists in the shunt path as shown in Fig. 6. Therefore, by designing the vertically stacked coupled square loops to satisfy $2M_0=L_{ESL}$, the inductance of the shunt path can be canceled to zero and the deterioration of filter performance due to ESL of the shunt path can be improved.

3. Design

Before designing the ESL-cancelling circuit using vertically stacked coupled square loops, ESL of the shunt path (L_{ESL}) must be cleared first. Figure 7 shows a reference configuration where a 1-μF film capacitor is connected in shunt between a differential pair on an FR4 substrate

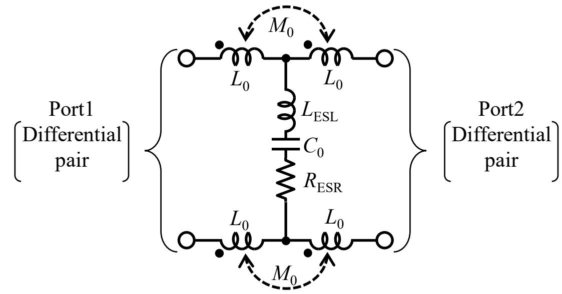


Fig. 5 An equivalent circuit of the configuration shown in Fig. 3.

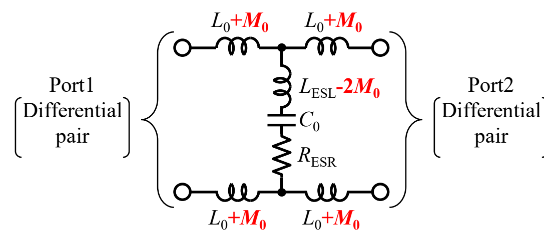


Fig. 6 A circuit obtained by applying an equivalent transformation to the magnetic couplings shown in Fig. 5.

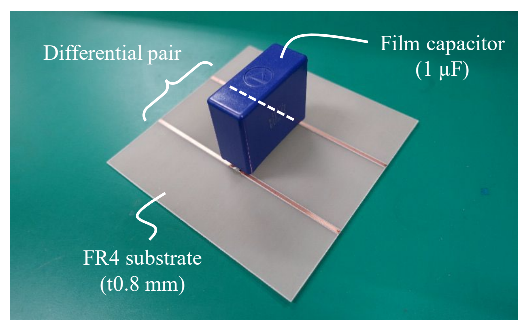


Fig. 7 A reference configuration.

(thickness: 0.8 mm, ε_r: 4.5, tanδ: 0.017, size: 100 mm×100 mm). Figure 8 shows measured S_{dd21} of the reference configuration, where S_{dd21} has minimum of -67.2 dB at a self-resonant frequency of 1 MHz. With these values, L_{ESL} and R_{ESR} can be obtained from

$$f_r = \frac{1}{2\pi\sqrt{L_{ESL}C_0}} \tag{1}$$

and

$$\mathrm{Min.}\, S_{dd21} = \frac{2R_{ESR}}{Z_0 + 2R_{ESR}}, \tag{2}$$

as L_{ESL}=25.3 nH and R_{ESR}=20mΩ, where f_r is the self-resonant frequency and Z_0 is the characteristic impedance of the differential pair (100Ω). An electromagnetic- (EM-) analysis model of the reference configuration can be then made as show in Fig. 9. The film capacitor is modeled by a metal block and wires, and RLC series circuits (R: $R_{ESR}/2$, L: $L_{EM}/2$, C: $2C_0$) are inserted in the middle of the wires. Note that L_{EM} is optimized to 11.4 nH which is smaller than L_{ESL} of 25.3 nH, since the metal block and the wires themselves have self-inductances those depend on their own shapes and sizes. Four 50Ω-Ports are placed between edges

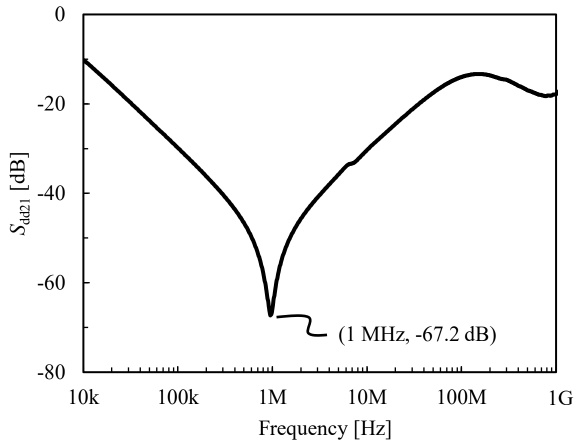


Fig. 8 Measured S_{dd21} of the reference configuration.

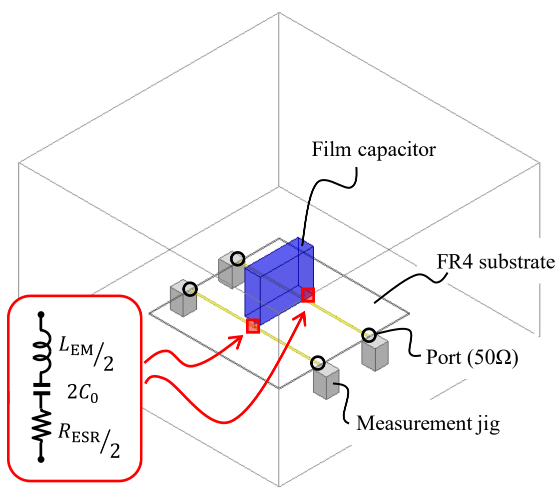


Fig. 9 The EM-analysis model of the reference configuration.

of the differential pairs and the measurement jigs modeled by metal blocks. EM-analysis results of S_{dd21} with initial and optimized values of L_{EM} are shown in Fig. 10 where S_{dd21} with optimized L_{EM} meets well with the measured result.

Initial size for the vertically stacked coupled square loops can be estimated by considering coupled loops as shown in Fig. 11, where two square loops of ideal lines with a side of a are placed h apart in the vertical direction from each other. By applying Biot-Savart law, mutual inductance between the loops (M) can be obtained from

$$M = \frac{\mu_0}{\pi}\Big[2\Big\{\sqrt{h^2+2a^2} - 2\sqrt{h^2+a^2} + h\Big\}$$
$$+2a\Big\{\operatorname{arctanh}\Big(\frac{a}{\sqrt{h^2+a^2}}\Big) - \operatorname{arctanh}\Big(\frac{a}{\sqrt{h^2+2a^2}}\Big)\Big\}\Big], \quad (3)$$

where μ_0 is permeability of a vacuum [5]. Fig. 12 shows $M(a)$ with h=0.8 mm, from which initial value of a can be estimated as 12.5 mm since $2M_0$=L_{ESL} is almost satisfied.

Figure 13 shows an EM-analysis model of the ESL-cancelling circuit for a film capacitor using vertically stacked coupled square loops and Fig. 14 show conductor patterns on the FR4 substrate. The model is based on the

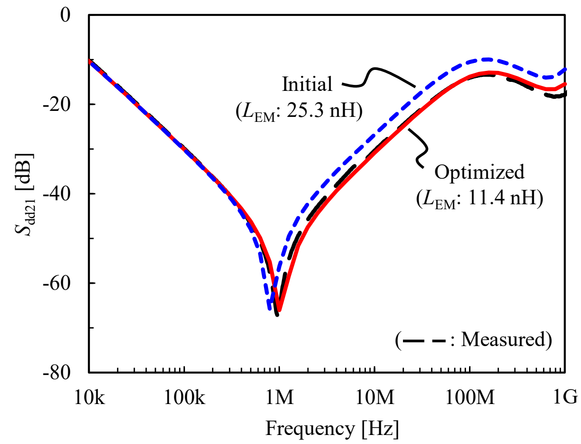


Fig. 10 EM-analysis results of S_{dd21} with initial and optimized L_{EM}.

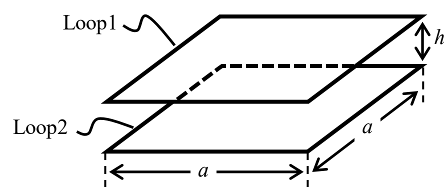


Fig. 11 A configuration to estimate initial size for the coupled loops.

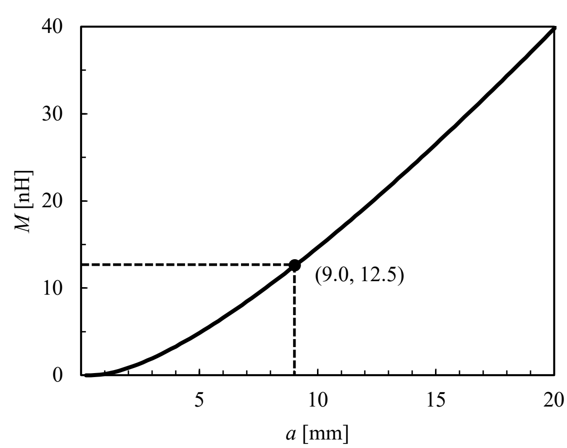


Fig. 12 EM-analysis results of S_{dd21} with initial and optimized L_{EM}.

model of the reference configuration shown in Fig. 9; two sets of vertically stacked coupled square loops of inner area of a×a mm^2 are added at the shunt connection points, and other settings are the same. Figure 15 shows EM-analysis results with initial and optimized values of a. Although even when a is its initial value of 9.0 mm, S_{dd21} is improved by 10 dB above the self-resonant frequency. However, further improvement can be expected since loops in the EM-analysis model lack part of them, unlikely to ideal closed loops shown in Fig.11, and so that mutual inductance is supposed to be smaller than expected from (3). In this study, a was optimized to 12.0 mm to meet the design goal of S_{dd21} being less than -40 dB from 1 MHz to 100 MHz, as shown by the solid line in Fig. 14.

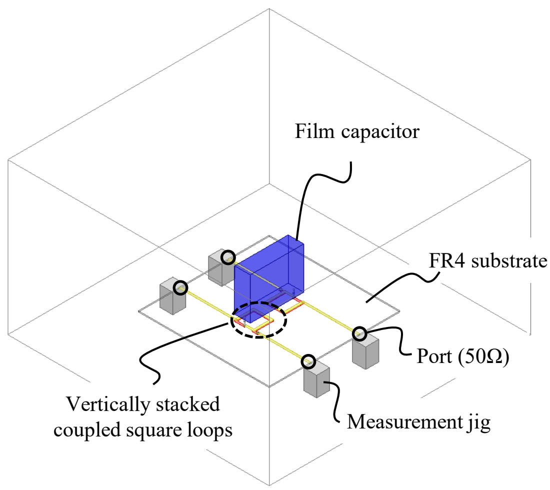
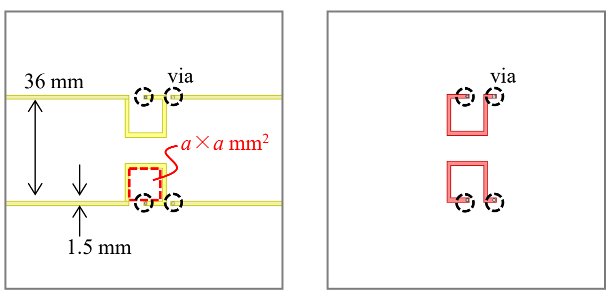


Fig. 13 The EM-analysis model of the ESL-cancelling circuit for a film capacitor using vertically stacked coupled square loops.



(a) Top view (b) Bottom view (transparent)

Fig. 14 Conductor patterns on the FR4 substrate in Fig. 13.

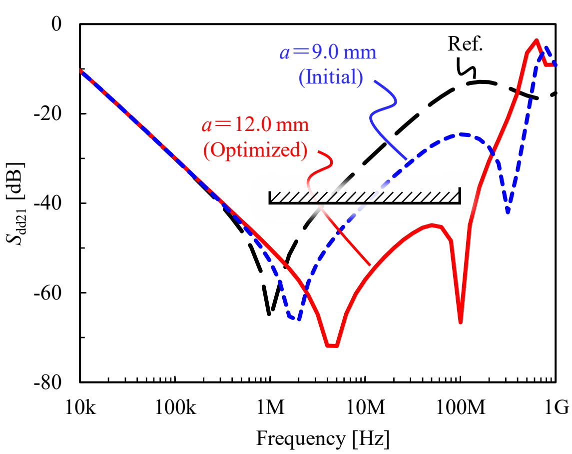


Fig. 15 EM-analysis results of the ESL-cancelling circuit with initial and optimized values of a.

4. Measurement

Figure 16 shows the fabricated prototype of the ESL-cancelling circuit using double-sided FR4 substrate (thickness: 0.8 mm, ε_r: 4.5, tanδ: 0.017, size: 100 mm×100 mm). Fig. 17 shows measured S_{dd21}, which meets well with the EM-analysis result, demonstrating that S_{dd21} is improved by more than 20-dB above the self-resonant frequency and that S_{dd21} is less than -40 dB from 1 MHz to 100 MHz.

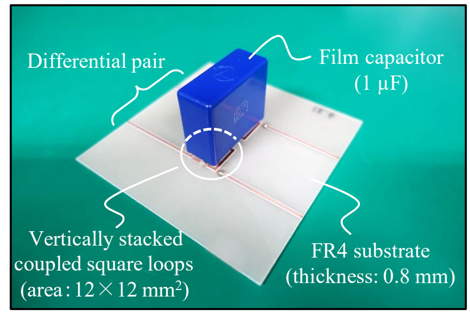


Fig. 16 The fabricated prototype of the ESL-cancelling circuit for a film capacitor using vertically stacked coupled square loops.

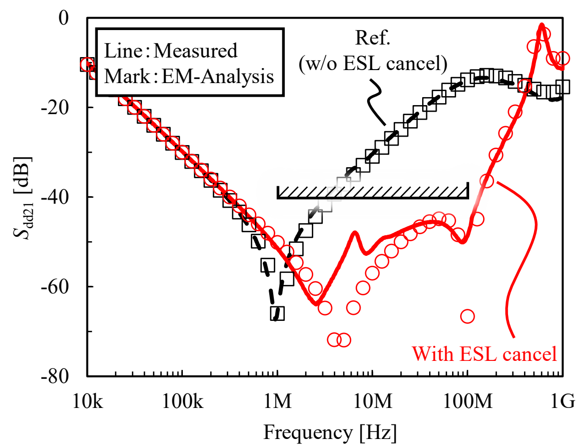


Fig. 17 Measured S_{dd21} of the fabricated prototype.

5. Summary

An ESL-cancelling circuit for a film capacitor using vertically stacked coupled square loops is reported in this paper. The configuration for a 1-μF capacitor was designed and fabricated according to Biot-Savart law and EM-analysis. The measured result showed good agreement with the EM-analysis result and demonstrated more than 20-dB improvement of S_{dd21} above the self-resonant frequency, indicating the validity of the proposed configuration.

References

[1] S. Wang, F. C. Lee, J. D. van Wyk, and J. D. van Wyk, "A study of integration of parasitic cancellation techniques for EMI filter design with discrete components," *IEEE Trans. Power Electron.*, vol. 23, no. 6, pp. 3094–3102, Nov. 2008.

[2] Y. Shiraki, N. Oka, Y. Sasaki, and H Oh-hashi, "High Performance broadband noise filter using inductance cancellation technique and various capacitors" in *Proc. 2016 International Symp. on Electromagn.Compat.*, pp. 570-575, Sept. 2016.

[3] S. Yoneda, K. Hirose, A. Kobayashi, Y. Sasaki, and C. Miyazaki, "A study for designing an ESL-Cancelling circuit for shunt capacitor filters based on the biot-savart law," in *Proc. IEEE Int. Symp. Electromagn. Compat. Signal/Power Integrity*, pp. 17–21, Aug. 2017.

[4] A. Kobayashi, S.Yoneda, Y. Sasaki, N. Oka, and H. Oh-hashi, "Surface mount shunt capacitor filters using bilateral magnetic coupling," in *Proc. IEEE Int. Symp. Electromagn. Compat. Signal/Power Integrity*, pp. 219-224, Aug. 2017.

[5] Y. Cheng and Y. Shu, "A new analytical calculation of the mutual inductance of the coaxial spiral rectangular coils," *IEEE Trans. Magn.*, vol. 50, no. 4, pp. 1–6, Apr. 2014.