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An ESL-Cancelling Circuit for a Shunt-Connected Film Capacitor Filter Using Vertically Stacked Coupled Square Loops

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SUMMARY An ESL-cancelling circuit for a shunt-connected film capacitor filter using vertically stacked coupled square loops is reported in this paper. The circuit is applicable for a shunt-connected capacitor filter whose equivalent series inductance (ESL) of the shunt-path causes deterioration of filter performance at frequencies above the self-resonant frequency. Two pairs of vertically stacked magnetically coupled square loops are used in the circuit those can equivalently add negative inductance in series to the shunt-path to cancel ESL for improvement of the filter performance. The ESL-cancelling circuit for a 1-μF film capacitor was designed according to the Biot-Savart law and electromagnetic (EM)-analysis, and the prototype was fabricated with an FR4 substrate. The measured result showed 20-dB improvement of the filter performance above the self-resonant frequency as designed, satisfying $S_{\rm dd21}$ less than −40 dB at 1 MHz to 100 MHz. This result is almost equivalent to reduce ESL of the shunt-path to less than 1 nH at 100 MHz and is also difficult to realize using any kind of a single bulky film capacitor without cancelling ESL.

key words: *equivalent series inductance (ESL), film capacitor, filter*

1. Introduction

A shunt-connected capacitor has 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 filter which simply consists of a capacitance connected in shunt between a differential pair. In practical, however, two parasitic components are unintentionally added in the shunt-path: equivalent series inductance (ESL) and equivalent series resistance (ESR), denoted as $L_{\rm ESL}$ and $R_{\rm ESR}$ in the figure. The filter works well as intended at frequencies below the self-resonant frequency of the shunt-path. At the frequencies above the self-resonant frequency, on the other hand, $L_{\rm ESL}$ becomes dominant, and the filter performance is deteriorated. This deterioration is principally unavoidable since the capacitor must have finite physical size and so that ESL of the shunt-path never becomes zero. Moreover, the deterioration would be unfortunately exacerbated when a bulky film capacitor is required for its advantage of having high voltage durability despite its relatively large physical size.

Recently, various configurations have been reported in [1]–[7] those can improve the deterioration caused by ESL as illustrated in Fig. 2. Note that when ESL is completely cancelled to zero, the filter performance above the self-resonant frequency remains at its ESR-dependent minimum. In the configurations, ESL in the shunt-path is equivalently cancelled by various means, and the improvement of the filter performance mainly depends on the amount of the ESL-cancellation. In [1], diagonally and shunt-connected two film capacitors called "X-capacitor-inductor structure" is reported which can be equivalently transformed by network theory into a one shunt-path circuit containing a negative inductance to cancel ESL. In [2]–[7], negative inductance is equivalently added in series to the shunt-path by magnetic coupling between various circuit components: a main line and a shunt-path [2], loops configured by via holes and lines connected to chip capacitors [3], a spiral-shaped line and a line connected to a three-terminal chip capacitor [4], vertically stacked coupled square loops [5], a chip capacitor itself and a main line [6], and a chip capacitor itself and bilateral lines adjacent to the capacitor [7].

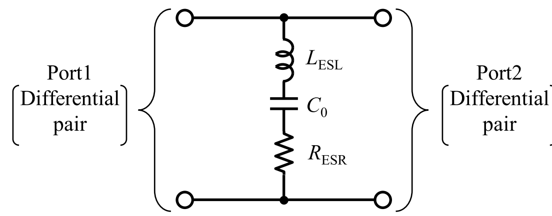

Fig. 1 A simplified configuration of a shunt-connected capacitor filter.

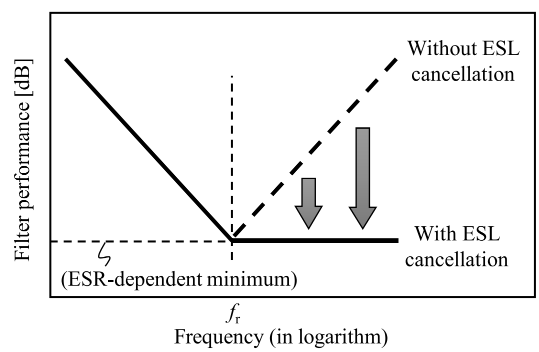

Fig. 2 Improvement of filter performance by an ESL cancellation.

In this paper, an ESL-cancelling circuit using vertically stacked coupled square loops for the shunt-connected film capacitor filter is proposed and the prototype evaluation result for a widely and commonly used typical 1-μF film capacitor (HCP1000V105K-S, Okaya Electric Industries Co., Ltd) is presented. At first, frequency characteristic of the

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filter circuit which simply consists of the 1-μF film capacitor connected between the differential pair is measured, and the measured result showed that self-resonant frequency is 1 MHz, and that the 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 the Biot-Savart law and electromagnetic (EM)-analysis. The designed result showed that the square loops with inner side of 12 mm can improve the filter performance by more than 20 dB at frequencies above the self-resonant frequency satisfying S_{dd21} less than −40 dB at 1 MHz to 100 MHz. Finally, the prototype configuration is fabricated using a double-sided FR4 substrate, and the measured result showed good agreement with the designed result, demonstrating the validity of the proposed circuit.

Compared with the referred configurations, the proposed circuit has the following new points of difference. The configuration in [1] is valid for two film capacitors and not applicable for a single film capacitor. In [2], a configuration for a single film capacitor is presented, however, coupled windings are employed those require larger area than required for vertically stacked coupled square loops in the proposed circuit. Configurations in [3]–[7] are an application for a chip capacitor connected between a single line and the GND, and so that it is not easy to apply them directly for a shunt-connected film capacitor filter.

Another point of difference is improvement of filter performance and required size for the magnetic coupling structures. For example, the configuration in [7] can improve filter performance above the self-resonant frequency by several dB with rather compact magnetic coupling structure, while the proposed circuit can improve filter performance by more than 20 dB at those frequencies with larger, but practically compact enough, magnetic coupling structure.

2. Configuration

Figure 3 shows the configuration of the proposed circuit and Fig. 4 shows the conductor patterns on the top and the bottom surfaces of the double-sided dielectric substrate in the figure. The film capacitor is connected in shunt between the differential pair, and square loops on the top and the bottom surfaces of the substrate are vertically stacked and electrically connected in series before and after the branch point of the shunt-path. Figure 5 shows the equivalent circuit of the configuration where the shunt-path is represented by series circuits of R_{ESR}, L_{ESL}, and C_0, and each set of vertically stacked coupled square loops are represented by magnetically coupled inductors connected before and after the branch point of the shunt-path with self-inductances of L_0 and mutual inductance of M_0.

In general, magnetic coupling in the direction indicated by the dots in Fig. 5 is known to be equivalent to the circuit transformation that adds positive inductance of $+M_0$ to the self-inductances and negative inductance of $-M_0$ in series to the shunt-path. By applying this circuit transformation to the magnetic couplings in Fig. 5, the equivalent circuit shown in Fig. 6 can be obtained where negative inductance of $-2M_0$ is added in the shunt-path. Therefore, by designing the vertically stacked coupled square loops to satisfy $2M_0 = L_{ESL}$, the ESL of the shunt-path can be ideally

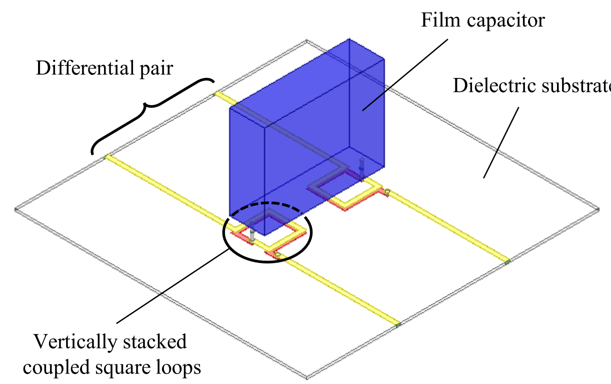
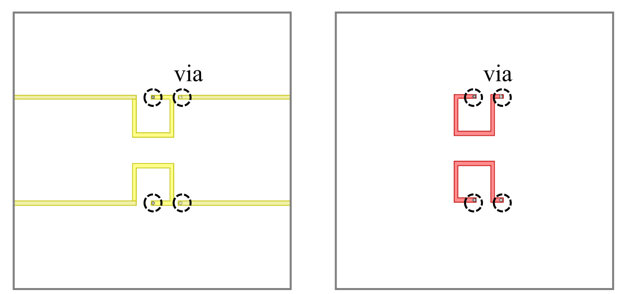


Fig. 3 The configuration of the proposed circuit.



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

Fig. 4 Conductor patterns on the dielectric substrate.

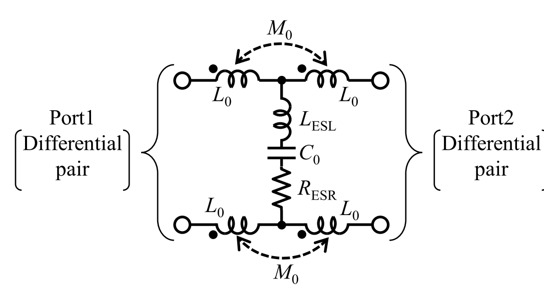


Fig. 5 The equivalent circuit of the configuration.

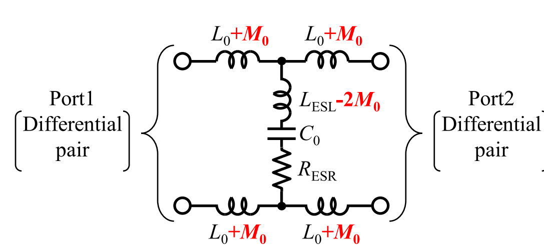


Fig. 6 The equivalent circuit obtained after applying equivalent circuit transformation to the magnetic couplings in Fig. 5.

cancelled to zero and then it can be expected to improve the deterioration of the filter performance due to the ESL of the shunt-path. Note that $+M_0$ added to the self-inductances in Fig. 6 are generally negligible when evaluating filter performance, since impedance of the added inductance is usually much smaller than the port impedance of the circuit.

3. Design

Before designing the loops, ESL of the shunt-path (L_{ESL}) must be cleared first. Figure 7 shows the reference configuration which simply consists of the 1-μF film capacitor connected in shunt between the differential pair with line width of 1.5 mm and line spacing of 36 mm on the FR4 substrate (thickness: 0.8 mm, ε_r: 4.5, tan δ: 0.017, size: 100 mm × 100 mm). In the measurement, the configuration is fixed 15 mm above the GND board by GND-connected measurement jigs, and port references are defined between the edges of the differential pairs and the jigs.

Figure 8 shows measured results of S_{dd21} of the reference configuration, where S_{dd21} has the minimum peak of −67.2 dB at the self-resonant frequency of 1 MHz. Using this result, L_{ESL} and R_{ESR} can be obtained from

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

and

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

as $L_{\mathrm{ESL}} = 25.3$ nH and $R_{\mathrm{ESR}} = 20$ mΩ, where f_r is the self-resonant frequency of 1 MHz and Z_0 is 100 Ω which is sum of the port impedance of the differential pair. The EM-analysis model of the reference configuration can be then modelled as shown in Fig. 9. The film capacitor is modelled by a metal block placed 5-mm above the substrate and wires where series circuits of $R_{\mathrm{ESR}}/2$, $L_{\mathrm{EM}}/2$, and $2C_0$ are inserted in the middle of them. Four 50 Ω-ports are placed between edges of the differential pairs and the measurement jigs modelled by metal blocks. EM-analysis results of S_{dd21} with the initial L_{EM} of L_{ESL} (25.3 nH) and the optimized L_{EM} of 11.4 nH are shown in Fig. 10 where S_{dd21} with the optimized L_{EM} meets well with the measured result. Note that the optimized L_{EM} is supposed to be smaller than L_{ESL}, because the metal block and the wires modelling the film capacitor have self-inductances themselves those depend on their sizes and shapes, and L_{ESL} is equal to the sum of L_{EM} and those self-inductances.

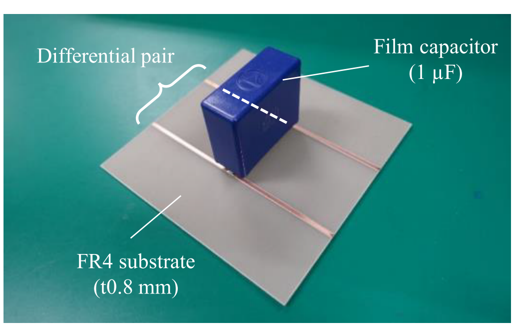


Fig. 7 The reference configuration.

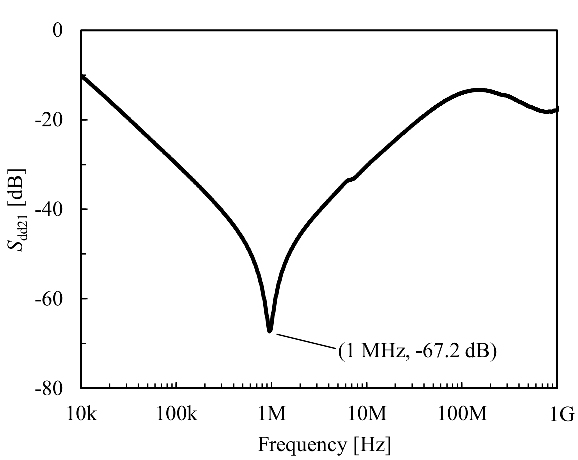


Fig. 8 Measured results of S_{dd21} of the reference configuration.

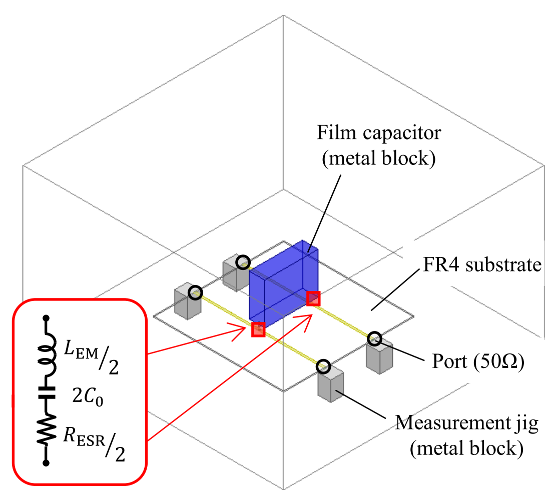


Fig. 9 The EM-analysis model of the reference configuration.

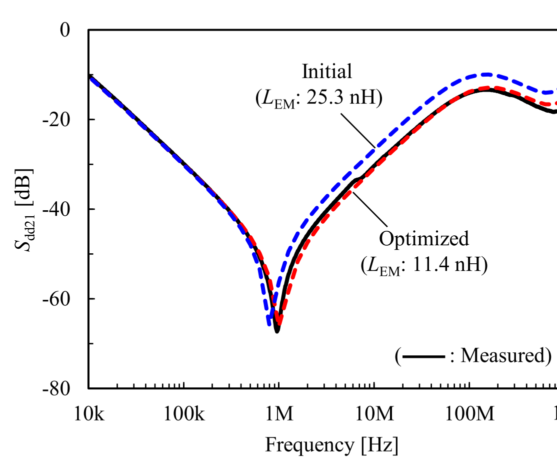


Fig. 10 EM-analysis results of S_{dd21} of the reference configuration with initial and optimized values of L_{EM}.

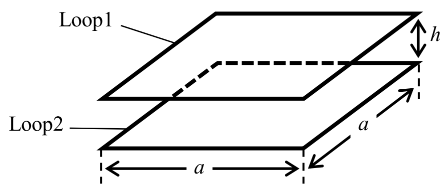


Fig. 11 The configuration of coupled loops of the ideal line.

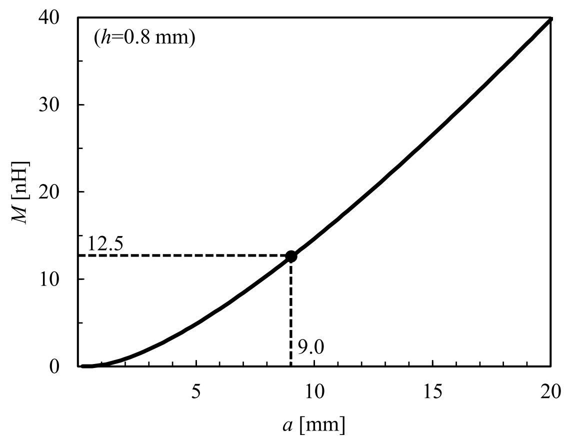


Fig. 12 Calculated results of M with $h = 0.8$ mm.

Initial size for the vertically stacked coupled square loops can be estimated from

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

which is the exact expression for the mutual inductance M of two square loops of an ideal line with a side of a placed h apart in the vertical direction as shown in Fig. 11, and the equation can be derived from applying the Biot-Savart law to the loops [8]. Note that the equation is valid only when two loops are overlapped without considering any interlayer misalignment. Figure 12 shows calculated results of M with h of 0.8 mm, from which the initial value of a can be estimated to be 9.0 mm, when M_0 is 12.5 nH and $2M_0 = L_{ESL}$ is almost satisfied.

Figure 13 shows the EM-analysis model of the ESL-cancelling circuit for the film capacitor using vertically stacked coupled square loops, and Fig. 14 shows conductor patterns on both sides of the double-sided FR4 substrate. The model is simply configured by adding two sets of the vertically stacked coupled square loops of the inner area of $a \times a\,\mathrm{mm}^2$ to the EM-analysis model of the reference configuration previously shown in Fig. 9.

Figure 15 shows EM-analysis results of S_{dd21} with a varied from the initial value of 9.0 mm to 13.6 mm. Although even when a is the initial value of 9.0 mm, S_{dd21} is improved by 10 dB above the self-resonant frequency. However, further improvement can be expected by increasing a,

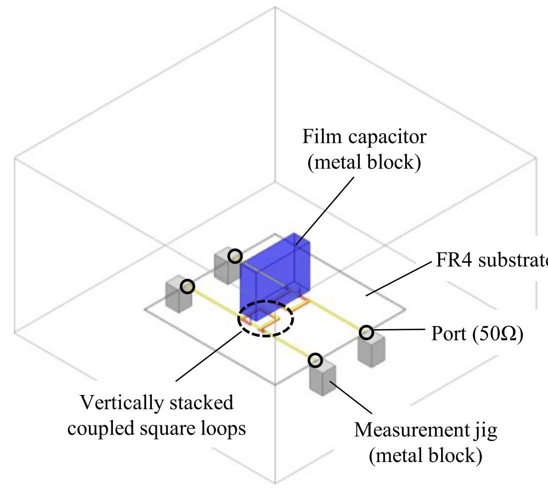
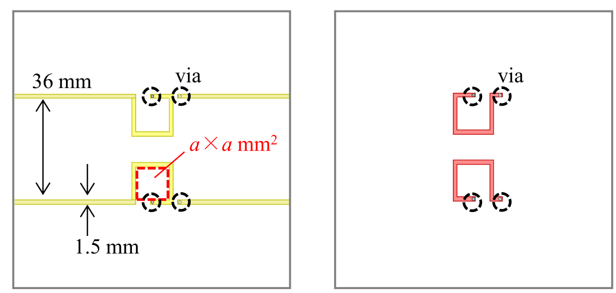


Fig. 13 The EM-analysis model of the proposed circuit.



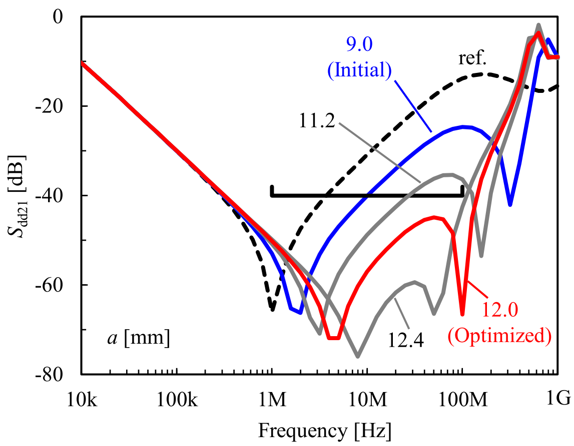
(a) Top view (b) Bottom view (transparent)

Fig. 14 Conductor patterns on the FR4 substrate.

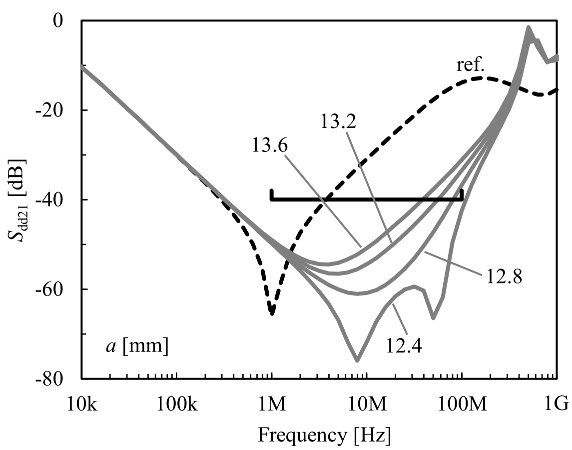
since the loops in the EM-analysis model are not closed unlikely to the ideal closed loops shown in Fig. 11, and so that mutual inductance of the loops in the EM-analysis model is supposed to be smaller than that of expected from (3). In Fig. 15(a), self-resonant frequency becomes higher and filter performance is improved as a increases from 9.0 mm to 12.4 mm. This response indicates that the ESL in the shunt-path is being cancelled as intended. In Fig. 15(b), however, the minimum peak of S_{dd21} disappears and the filter performance is deteriorated as a increases from 12.4 mm to 13.2 mm. This response indicates that the ESL in the shunt-path is over-cancelled leaving unnecessary negative inductance in the shunt-path. 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 to 100 MHz. Note that conductive planes or objects placed adjacent to the coupled loops generally defect their magnetic coupling and reduce their mutual inductance. Therefore, the GND plane and the film capacitor should not be unnecessarily adjacent to the coupled loops on the substrate in a practical use.

4. Measurement

Figure 16 shows the fabricated prototype of the ESL-cancelling circuit using double-sided FR4 substrate (ε_r: 4.5, $\tan\delta$: 0.017, thickness: 0.8 mm, size: 100 mm × 100 mm).

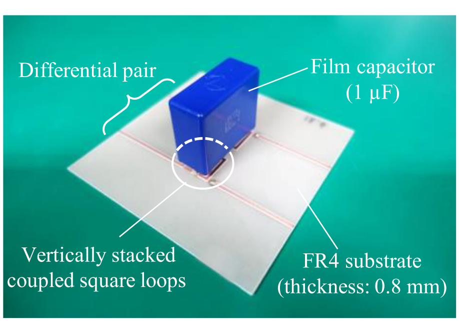


(a) a: 9.0 mm (initial) to 12.4 mm

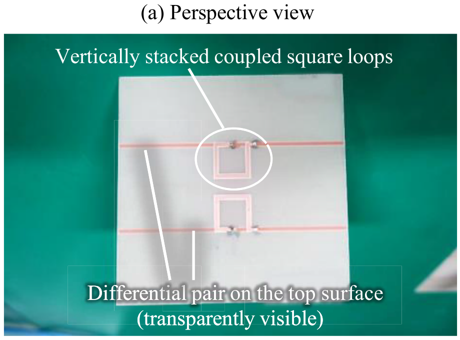


(b) a: 12.4 mm to 13.6 mm

Fig. 15 EM-analysis results of S_{dd21} of the proposed circuit.



(a) Perspective view



(b) Bottom view

Fig. 16 The fabricated prototype of the proposed circuit.

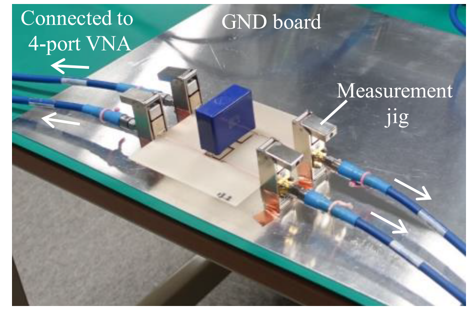


Fig. 17 The measurement system.

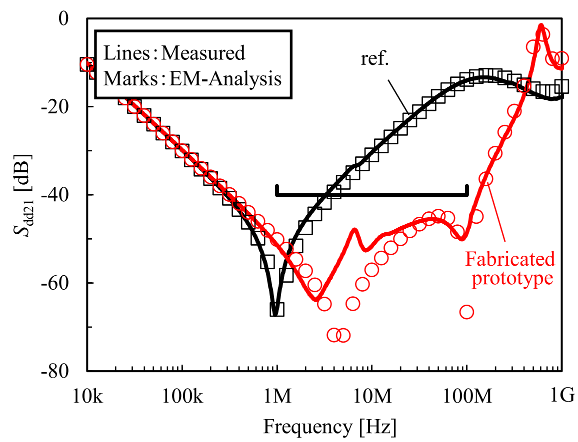


Fig. 18 Measured results of S_{dd21} of the fabricated prototype.

Note that in Fig. 16(b), the differential pair on the top surface of the substrate is transparently visible in the bottom view of the substrate. Figure 17 shows the measurement system where the fabricated prototype is fixed 15 mm above the GND board by the GND-connected measurement jigs and is connected to the 4-port VNA with four coaxial cables.

Figure 18 shows measured results of S_{dd21} of the fabricated prototype those are in good agreement with the EM-analysis results, showing more than 20-dB improvement of S_{dd21} above the self-resonant frequency satisfying S_{dd21} less than −40 dB from 1 MHz to 100 MHz. A slight discrepancy between the measured and the EM-analysis results of the fabricated prototype can be seen at 3 to 10 MHz, whose one possible reason may be the frequency dependence of the ESR of the film capacitor which was not considered in the current EM-analysis model to simplify the analysis.

5. Discussion

In this section, residual ESL in the shunt-path of the fabricated prototype is discussed. Figure 19 shows the SPICE models to evaluate filter performance of the shunt-connected capacitor filter. In the left circuit, the series circuit of R_{ESR}, L_{SPICE}, and C_0 is connected in shunt between the input and the output impedances of Z_{in} and Z_{out}, while the right circuit has no shunt-path. The filter performance of the left circuit,

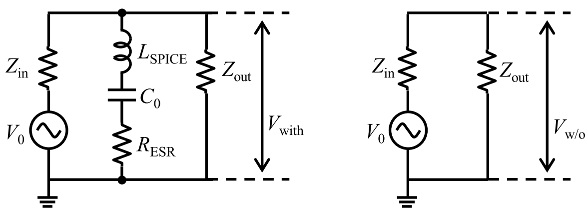


Fig. 19 The SPICE models to evaluate the filter performance.

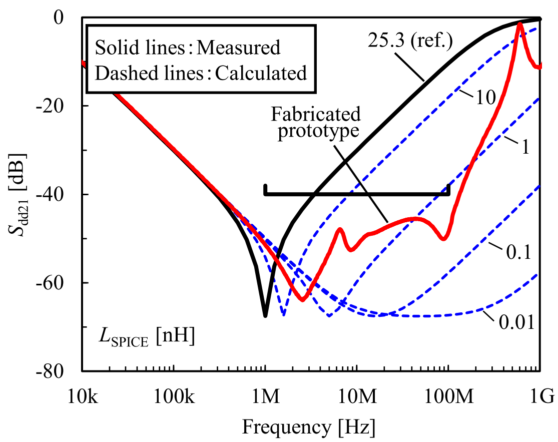


Fig. 20 Calculated results of S_{dd21} with Z_{in} and Z_{out} of 100 Ω, R_{ESR} of 20 mΩ, C_0 of 1 μF, and various L_{SPICE} of 10, 1, 0.1, and 0.01 nH.

represented by S_{dd21}, can be calculated by $V_{with}/V_{w/o}$ which is a ratio of the voltages at Z_{out} with and without the shunt-path.

Figure 20 shows calculated results of S_{dd21} in dashed lines with Z_{in} and Z_{out} of 100 Ω, R_{ESR} of 20 mΩ, C_0 of 1 μF, and various L_{SPICE} of 10, 1, 0.1, and 0.01 nH. For comparison, the measured results of the fabricated prototype and the reference configuration are also shown in solid lines in the figure. It can be obviously seen in the figure that the filter performance above the self-resonant frequency improves as L_{SPICE} decreases.

These results are applicable for estimating residual ESL in the shunt-path of the fabricated prototype. At 100 MHz, for example, the measured result of S_{dd21} of the fabricated prototype becomes less than −40 dB, while the calculated result with L_{SPICE} of 1 nH is almost −40 dB. This comparison implies that the residual ESL in the shunt-path of the fabricated prototype is equivalently cancelled to less than 1 nH at 100 MHz.

6. Conclusion

In this paper, an ESL-cancelling circuit for a film capacitor using vertically stacked coupled square loops was proposed and evaluated result was reported. The configuration for a 1-μF capacitor connected in shunt between a differential pair was designed according to the Biot-Savart law and EM-analysis. The prototype configuration was then fabricated with a double-sided FR4 substrate, and the measured result showed good agreement with the EM-analysis results, showing more than 20-dB improvement of S_{dd21} above the self-resonant frequency satisfying S_{dd21} less than −40 dB from 1 MHz to 100 MHz. These characteristics are considered difficult to realize in principle without the ESL-cancelling technique, because a film capacitor, which is generally bulky, usually has relatively large ESL that is not negligible above MHz frequency band.

For a practical use of the proposed configuration, there are still some items to be considered: miniaturization of the loops, extending filter performance improvement to the higher frequencies, modelling the equivalent circuit, estimating electromagnetic couplings from adjacent circuits and conductor patterns, and suppressing deterioration by interlayer misalignment, for example.

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