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Analysis of a Low-Pass Filter Employing a 4-Pin Capacitor

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***Abstract*—Capacitors with two or three leads tend to make poor low-pass filters at high frequencies (e.g., >100 MHz) due to the mutual inductance between the input and output sides of the filter. This paper proposes a four-lead low-pass filter capacitor design that minimizes the magnetic flux coupling between the input and output. Measurements of a prototype capacitor confirm that it performs significantly better than a typical two-lead capacitor at high frequencies.**

***Index Terms*—Capacitor, filter, mutual inductance.**

I. INTRODUCTION

Low-speed input–output (I/O) traces leaving a PCB are often filtered to keep high-frequency noise on the signal traces from exiting the printed circuit board (PCB) on an attached cable. Typically, a low-pass filter in the form of a single capacitor connected between the signal trace and the return plane of the PCB is used. These types of filters are usually effective below a few hundred megahertz. However, the performance of these filters degrades significantly at frequencies above the first "self-resonant" frequency of the capacitor. The primary reason these types of filters become ineffective is that the current flowing through the capacitor couples magnetic flux from one side of the filter to the other. The impact of this mutual inductance has been studied before in [1]–[3] and has been shown to be the dominant factor in determining the filter behavior at high frequencies. This paper evaluates a low-pass filter made with a 4-pin capacitor that minimizes this mutual inductance and exhibits significantly improved performance at high frequencies.

II. BACKGROUND INFORMATION ON LOW-PASS FILTERS

A schematic of a typical low-pass filter on a signal trace is shown in Fig. 1. The schematic has a source voltage V_s with a source resistance R_s driving load resistance R_L. A shunt capacitor acts as a low-pass filter. The capacitor has an equivalent series resistance, R, and a capacitance, C, that are relatively independent of the mounting geometry. Mounted capacitors also have inductance. For surface mount technology (SMT) capacitors, this inductance is normally dominated by current loops associated with the mounting of the device. The source-side loop and the load-side loop have a self inductance of L_1 and L_2, respectively. Additionally, magnetic flux from the source-side loop that couples the load-side loop results in a mutual inductance M between the two halves of the circuit. This mutual inductance is primarily a function of the width and length of the capacitor, and the leads and vias that are parts of both the input and output loops [3].

Filter designers often model the self and mutual inductances associated with a filter capacitor using a single "equivalent series inductance" (ESL). The concept of ESL simplifies the filter analysis by eliminating the two (L-M) components in Fig. 1 and assigning the value of the ESL to M. This simplified circuit yields results identical to the more complex circuit in Fig. 1 when L and M are approximately equal (i.e., most of the magnetic flux in the capacitor connection couples both the input and the output of the filter). However, in a well-designed capacitor filter, the value of M should be much lower than L. In this situation, models employing a single ESL for the capacitor will fail to predict the correct high-frequency response.

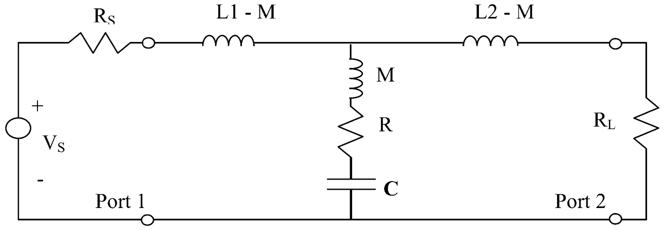

Fig. 1. Equivalent circuit for a single-capacitor low-pass filter.

A bode plot of the transfer coefficient $|S_{21}|$ for the circuit in Fig. 1 is shown in Fig. 2 for the case $L_1 = L_2 = L$ and $R_S = R_L = Z_0$. The equations shown, assume that the equivalent series resistance, R, is small and that $Z_0 \gg \sqrt{(L+M)/C}$. The impact of the mutual inductance on the voltage transfer coefficient at high frequencies is apparent from the plot. Above the resonance frequency, $1/(MC)^{(1/2)}$, $|S_{21}|$ increases proportional to M. Above the frequency $Z_0/(L+M)$, $|S_{21}|$ peaks at a value equal to $2M/(L+M)$. If the mutual inductance between the source-side loop and the load-side loop is reduced, then the voltage transfer characteristics will improve (i.e., there will be less coupling) at high frequencies.

III. PROTOTYPE LOW-M 4-PIN CAPACITOR

Most of the mutual inductance in a capacitor filter occurs at points where a thin conductor is shared by both the input and the output circuits. In a two-lead capacitor, both leads are shared. A three-lead capacitor has one input lead, one output lead, and a shared lead that is primarily responsible for the mutual inductance. In order to eliminate the sharing of leads between the input and output, it is necessary for a capacitor to have at least four leads. Four-lead capacitors have been proposed in the past (e.g., [4]) as a means of reducing equivalent series inductance.

In order to achieve the lowest possible inductance, a capacitor filter must not only have four leads, but it must also ensure that the magnetic flux wrapping these leads does not couple both the input and the output circuits. The design of a prototype low-mutual inductance (Low-M) four-lead capacitor is illustrated in Figs. 3 and 4. The interior of the Low-M capacitor is depicted in Fig. 3. The key feature of this design is that the only loop area shared by both the input and the output is between the capacitor plates. For typical SMT capacitor packages, the flux between the plates results in no more than a few picohenries of inductance. By maximizing the distance between the input and output leads, the amount of magnetic flux that wraps both the input and output circuits is minimized and mutual inductances below 1 nH can be achieved.

A prototype capacitor built to demonstrate the effectiveness of the design in Fig. 3 is shown in Fig. 4. This surface mount package actually contains two capacitors so there are four leads on each side rather than two. Each capacitor plate is connected to two pins. "Input" pins are on one side of the package and "output" pins are on the opposite side. The capacitance between the signals A and $\overline{A}$ is achieved by interleaving conductive plates connected to signal A and $\overline{A}$ inside the component. For this study, only one of the capacitors in the package was evaluated. The pins of the other capacitor (B, $\overline{B}$) were left unconnected.

To reduce the mutual inductance between the source-side and load-side loops, the dimensions of the filter are as follows: 6.35 mm in

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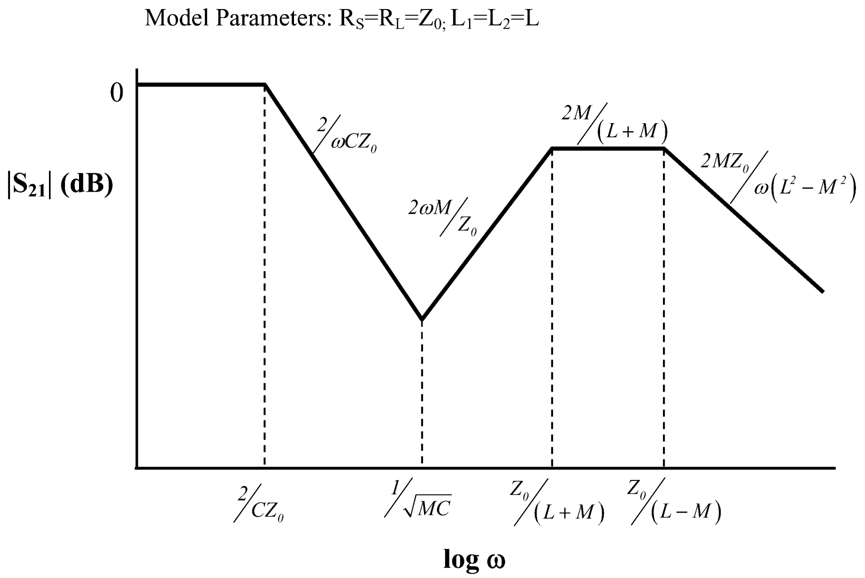

Fig. 2. Bode plot of $|S_{21}|$ for the low-pass filter in Fig. 1.

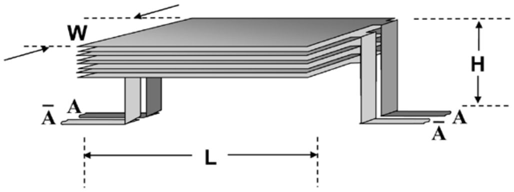

Fig. 3. Interior of prototype low-M capacitor.

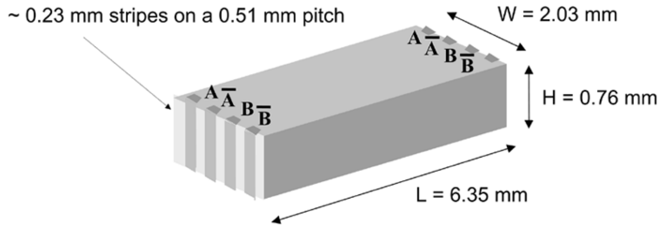

Fig. 4. Prototype Low-M capacitor package.

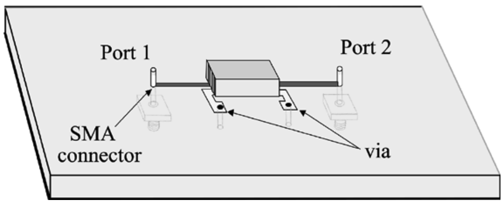

Fig. 5. Test board with low-M capacitor.

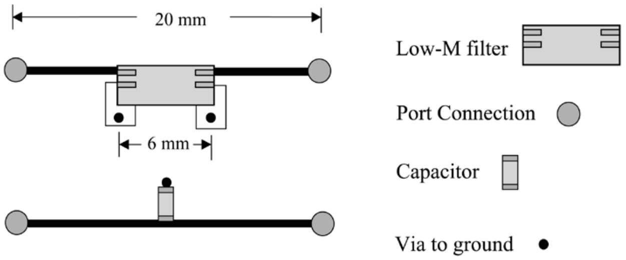

Fig. 6. Top-down view of two different filter configurations; low-M filter, and one-capacitor filter.

length, L, 0.76 mm in height, H, and 2.03 mm in width, W. The length of the component, L, is long compared to the other dimensions to reduce the coupling between the input pins and the output pins. The height of the component is minimized for the same reason. The width of the component, W, is not critical, but is kept small so that the component will take up less space on a PCB. Since the input side of this filter capacitor does not share any leads with the output side, there are no places where a strong magnetic flux couples both the input and output current loops.

IV. LABORATORY MEASUREMENTS OF THE LOW-M FILTER

The low-M capacitor was mounted on a test board as shown in Fig. 5. The bottom of the test board was a solid copper ground plane. SMA connectors were placed on the test board and connected to both ends of a 20-mm microstrip trace. The PCB dielectric was 1-mm thick. On both sides of the filter, one electrical contact was connected to the signal trace A while the other electrical contact $\overline{A}$ was connected to the ground plane. To determine the effectiveness of the low-M capacitor filter, the $|S_{21}|$ was measured with a network analyzer. For comparison purposes, a low-pass filter made from a standard two-lead SMT capacitor (Fig. 6) with the same nominal value was also measured. The measured results are shown in Fig. 7.

The measured results show that the prototype low-M filter outperforms a typical two-lead capacitor at high frequencies by approximately 10–15 dB. The M-C resonance of the low-mutual inductance filter is at a higher frequency due to the lower mutual inductance between the input and output sides of the filter. The magnitude of S_{21} exhibits a peak around 5 GHz due to a half-wave resonance of the connecting microstrip traces.

In order to try to reduce the mutual inductance of the two-lead capacitor filter, additional vias were added to the capacitor mounting pads. This resulted in a slight decrease in the mutual inductance, but the capacitor still performed significantly worse than the four-lead capacitor above 100 MHz. This demonstrates that the flux wrapping the body of the capacitor was the primary contributor to the coupling rather than the flux wrapping the connecting vias.

By examining the break points in the plot shown in Fig. 7 and comparing them to the Bode plot in Fig. 2, it is possible to determine the

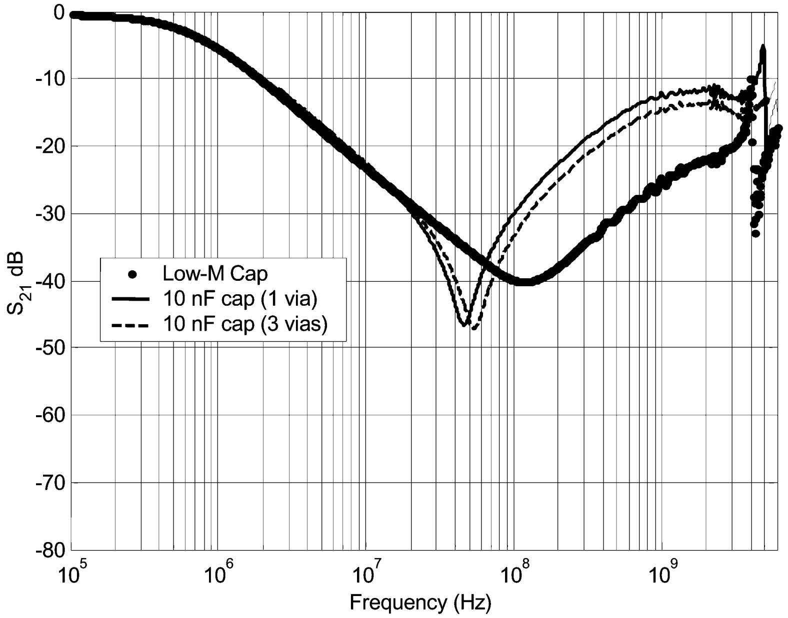

Fig. 7. Measured results for the filter configurations shown in Fig. 6.

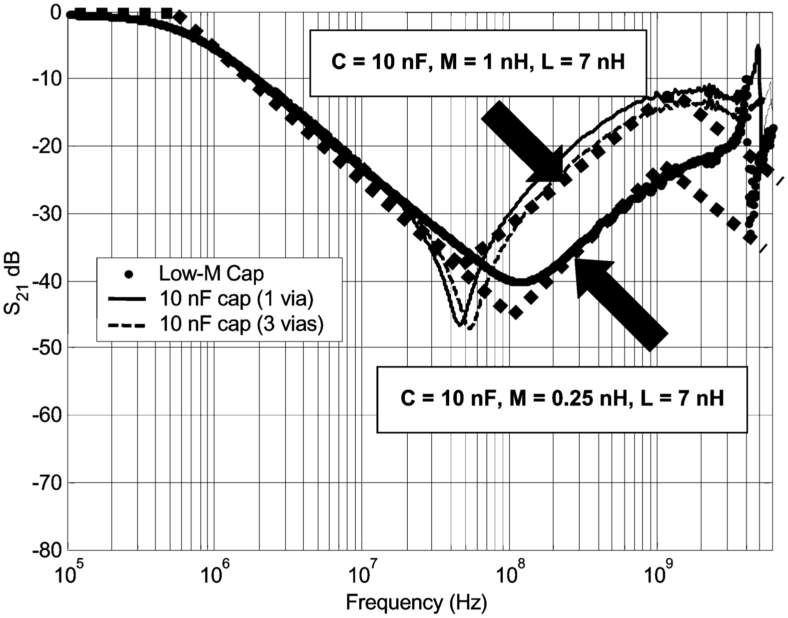

Fig. 8. Measured filter response overlaid with Bode plot indicating values of C, M, and L.

effective values of the self and mutual inductances. Values obtained in this manner were

$$\begin{aligned}\text{Two-lead capacitor} : \mathrm{C} &= 10 \text{ nF}, \quad M = 1 \text{ nH}\\ L &= 7 \text{ nH}\\ \text{Low-}M\text{ capacitor} : C &= 10 \text{ nF}, \quad M = 0.25 \text{ nH}\\ L &= 7 \text{ nH.}\end{aligned}$$

Fig. 8 shows the Bode plots using these values overlaying the measured data. Note that the self inductances (mostly associated with the connections to the board) are approximately the same. The lower mutual inductance of the low-M capacitor is responsible for the significantly improved filter response above 100 MHz.

V. CONCLUSION

The performance of low-pass filters made from a single two-lead capacitor is limited by the mutual inductance between the input and output sides of the filter. Capacitors with four leads that are designed to reduce the magnetic flux coupled from the input to the output can be used to build much more effective low-pass filters than capacitors with two or three leads. The prototype capacitor evaluated in this paper provided an additional 10–15 dB of attenuation at frequencies above 100 MHz compared to a standard two-lead capacitor.

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