Improving the High-Frequency Attenuation of Shunt Capacitor, Low-Pass Filters

C. N. Olsen, T. P. Van Doren, T. H. Hubing, J. L. Drewniak, R. E. DuBroff
Electromagnetic Compatibility Laboratory
Department of Electrical and Computer Engineering
University of Missouri – Rolla
Rolla, Missouri 65409-0040

Abstract: Circuit board mounted, shunt capacitive filters are less effective at high frequencies because of the mutual inductance (M) that exists between the input and output ports. An approximate expression for the mutual inductance is $M = (\mu h/2\pi)\ln(h/a)$; where h = via length and a = radius of the via connecting the capacitor to the return plane. The reduced mutual inductance associated with the new, three-terminal, surface-mounted capacitor results in more than 15 dB increased attenuation compared to two-terminal capacitors over the 0.3 – 6.0 GHz range with 50 Ω source and load terminations.

I. Introduction

Shunt-capacitor, low-pass, two-port filters attempt to allow high-frequency (HF) noise currents to return to their source without passing through the output port. Parasitic elements dominate the impedance of the capacitor beyond a series resonant frequency, limiting the effectiveness of the filter. The dominant parasitic element is usually described as the sum of the capacitor equivalent series inductance (ESL) and the self-inductance of the leads, or traces, connecting the capacitor into the circuit [1], [2]. Since mutual magnetic flux coupling dominates the ESL, it is more appropriate to name the parasitic element mutual inductance, M. The mutual inductance can be distinguished from the ESL of the capacitor by shorting out the capacitor and then measuring the magnetic coupling at HF. At the series resonant frequency, the equivalent series resistance of the shunt connection, or ESR, determines the impedance [3]. The measured results for well-mounted, two-terminal capacitors, three-terminal capacitors and via shorts are presented with applicable models.

II. Equivalent Circuit

A schematic diagram for the shunt capacitor test configuration is shown in Figure 1(a). The T-equivalent transformer representation is shown in Figure 1(b), where R = ESR, $Z_S = Z_L = Z_0$, and $L_1 = L_2 = L$.

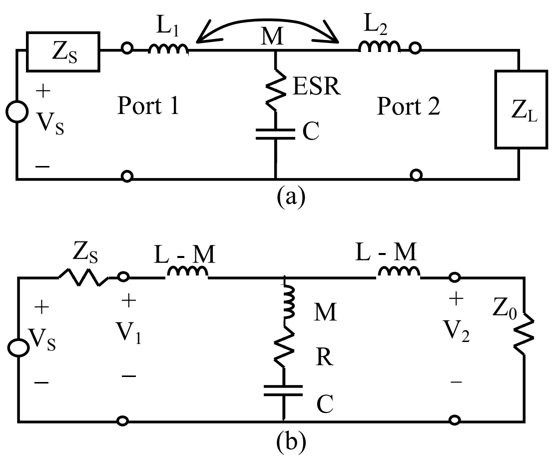


Figure 1. Shunt capacitor equivalent circuits: (a) Original version and (b) using the transformer T-equivalent.

The equation for the S_{21} of Figure 1(b) is

$$\frac{V_2^-}{V_1^+} = \frac{2Z_0\left(R + j\omega M + \frac{1}{j\omega C}\right)}{\left(Z_0 + j\omega L + \frac{1}{j\omega C}\right)^2 - \left(R + j\omega M + \frac{1}{j\omega C}\right)^2} \qquad (1)$$

and can be used to model the filter, with known parameters, or to extract values from the measured data. Figure 2 illustrates the asymptotic bode plot derived from equation(1).

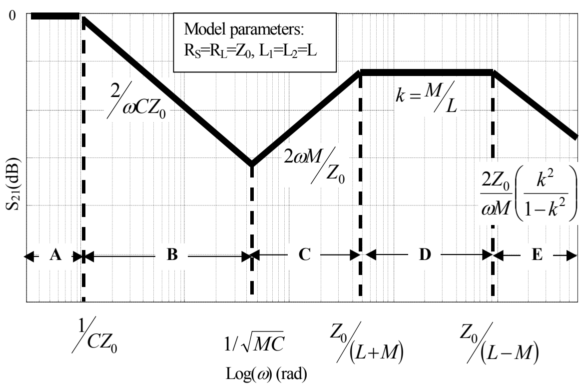


Figure 2. Asymptotic Bode Plot (S_{21}) for the Shunt Capacitor Equivalent Circuit

The asymptotic bode plot of $|S_{21}|$ for the shunt capacitor filter model is segmented by frequency regions. Each frequency region can be defined by an equation with a ± 20 or 0 dB/decade slope, as shown in Figure 2. The bode plot shows the MC series resonant frequency and a high-frequency, maximum $|S_{21}|$ level approximately equal to the coupling coefficient, *k*, between the input and output loops of the two port network.

III. Theory

The mutual inductance, M, was derived using the Biot-Savart Law for each segment of the input loop, then integrating the magnetic flux passing through the output loop surface using Gauss's Law. The resulting magnetic flux, Ψ_M, was divided by I, the current of the source loop, to yield the mutual inductance M [4], [5]. A simple approximation to the long, analytic formula is

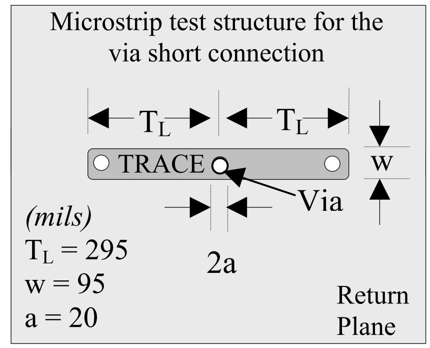
$$M = \frac{\mu h}{2\pi}\ln\left(\frac{h}{a}\right) \quad ; \qquad (2)$$

where a = via radius, and h = via length to the return plane. The simplified formula assumes $a < h < 10a$, and, $a << T_L$, where T_L is the transmission line length connected to the via, see Figure 3(a). The derivation neglects the capacitor and models only the mutual inductance caused by the two loops having the via as a common boundary.

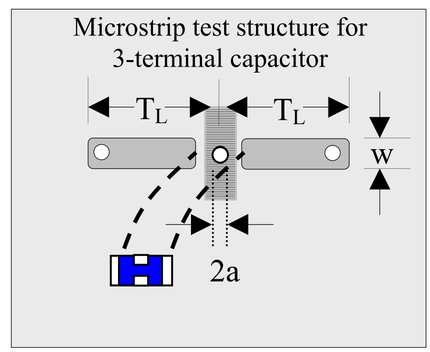
IV. Experiment vs. Theory

The test setup used a milled, 50 Ω microstrip transmission line attached through SMA connectors to a HP8753D network analyzer. A 1.5 *cm* long microstrip line was centered on a 5 *cm* square board. The board thicknesses were 10, 45, and 60 *mils*.

Measurements were made on a via short and a three-terminal capacitor mounted directly on the transmission line, as shown in Figure 3(a, b). The measured $|S_{21}|$ curves are nearly identical above 1 GHz, implying any ESL of the capacitor has a negligible impact versus the mutual inductance of the mounting geometry, see Figure 4(a, b).



(a)

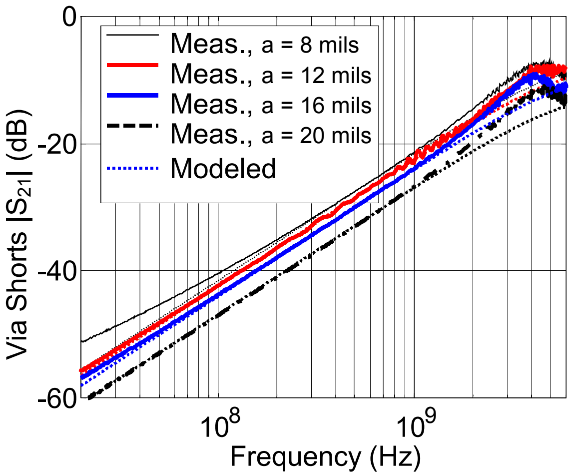


(b)

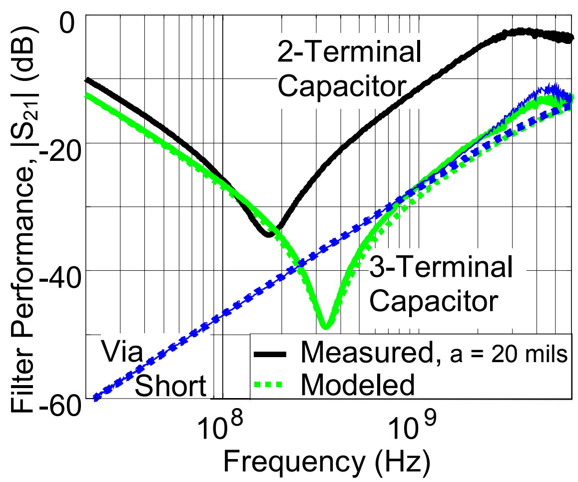
Figure 3. Microstrip test structure for (a) Via Short, and, (b) 3-terminal Capacitor.

Using circuit parameters extracted from measured data, the analytical expression for S_{21} (equation (1)) yields results shown in Figure 4(a, b) that validate the equivalent circuit through 3 GHz, and show it useful through 6 GHz. For the 3-terminal capacitor, C = 1.28 nF, ESR = 0.09 Ohms, L = 0.8 nH, and M = 0.172 nH. The via short model is the same as the capacitor model shown in Figure 1(a) with ESR and C removed.

The theoretical value of M for the 3-terminal case is identical to the via short, about 0.185 *nH*, see equation (2). However, using different values for *h* and *a* for a 3-terminal capacitor, M can easily vary between 0.052 *nH* and 0.444 *nH*, and can rise beyond 0.902 *nH* for 2-terminal capacitors, see Table 1. The 2-terminal capacitor was well mounted with one terminal on the transmission line and the other terminal on a pad



(a)



(b)

Figure 4. Measured and Modeled $|S_{21}|$ of (a) Via Shorts, and (b) Shunt Capacitors with Via Shorts.

containing a connection to the return plane. Though mounted better than is usually possible, the 2-terminal capacitor resulted in 15 dB less attenuation compared to a 3-terminal capacitor, using the same via diameter and via length (Figure 4(a, b) and Table 1).

The via shorts in Figure 4(a) illustrate measurements in agreement with equation (1) and Figure (2), where the capacitor is replaced by a short. Specifically, halving the via diameter results in nearly a 6 dB increase in the mutual inductance.

Table 1. Calculated and Measured Mutual Inductance for Various Shunt Capacitor and Via Short Geometries

h,a (mils): Shunt Type	M*(nH)* Calculated from Eq. 2	M*(nH)* From measured data
45,20: 0805 Capacitor Part #ECU-V1H1102KBN	N/A	0.902
45,20: 0612 Capacitor Part # 0612Y104KXX	N/A	0.606
45,20: 3-T Cap., 1 via Part # CKD110JB1E102S	0.185	0.172
45,20: 3-T Cap., 3 vias Part # CKD110JB1E102S	N/A	0.052
45,10: Via Short	0.344	0.293
45,20: Via Short	0.185	0.179
60,10: Via Short	0.546	0.444
60,20: Via Short	0.335	0.284
60,53: Via Short	0.168*	0.099
10,10: Via Short	0.028*	0.020
10,20: Via Short	0.016*	0.009

* Long equation used (long equation is not presented here, see [5])

V. Conclusion

The HF performance of a shunt low-pass filter is determined by the mutual inductance. Since the 3-terminal capacitor adds minimal magnetic flux coupling area, it is as good as a short at HF and superior to well-mounted 2-terminal capacitors by at least 15 dB. The mutual inductance M may be estimated using a simple formula, allowing designers to better control the HF performance of low-pass filters.

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