

## Parasitic Capacitance Cancellation in Filter Inductors

Timothy C. Neugebauer and David J. Perreault

Massachusetts Institute of Technology  
Cambridge, MA 02139  
Email: neugebat@mit.edu

**Abstract**—This paper introduces a technique for improving the high-frequency performance of filter inductors and common-mode chokes by cancelling out the effects of parasitic capacitance. This technique uses additional passive components to inject a compensation current that cancels the parasitic current, thereby improving high-frequency filtering performance. Two implementation approaches for this technique are introduced. The first implementation achieves cancellation using an additional small winding on the filter inductor and a small capacitor. This approach is effective where very high coupling of the windings can be achieved or where only moderate performance improvements are required. The second implementation utilizes a small RF transformer in parallel with the filter inductor to inject cancellation currents from the compensation capacitor. This technique requires an additional component (the transformer), but can provide a high degree of cancellation. Experimental results confirm the theory in both implementations.

### I. INTRODUCTION

Filter inductors and common-mode chokes suffer from both parasitic resistance and capacitance. Winding resistance and core loss lead to parasitic resistance, while parasitic capacitance arises from capacitance between winding turns and from winding-to-core capacitance. The distributed parasitic components can be lumped together to form the lumped-parameter model for an inductor shown in Fig. 1a [1]–[4]. The impedance magnitude of a practical inductor as a function of frequency is illustrated in Fig. 1b. The parasitic capacitance dominates the impedance above the self-resonant frequency of the inductor (typically 1-10 MHz for power electronics applications, but sometimes lower for ungapped common-mode chokes). This parasitic capacitance reduces the impedance of an inductor at high frequencies, and hence reduces its effectiveness for high frequency filtering.

This paper introduces a technique for improving the high-frequency performance of filter inductors by cancelling out the effects of the parasitic capacitance. This technique uses

additional passive components to inject a compensation current that cancels the current flowing through the inductor parasitic capacitance, thereby improving high-frequency filtering performance. The proposed technique is related to strategies that have been exploited for reducing common-mode noise in certain power supply topologies [5]–[10], and is applicable to a wide range filtering and power conversion applications where the parasitic feedthrough of magnetic components is an important consideration.

The paper is organized as follows: Section II outlines the proposed capacitive cancellation technique, and illustrates one simple implementation method. Section III presents an experimental evaluation of this implementation approach, and identifies the factors that limit its performance. Section IV presents an alternative implementation that overcome the limitations of the simple implementation along with experimental validation of it. Finally, section V concludes the paper.

### II. CAPACITANCE CANCELLATION

The proposed technique improves the performance of magnetic components (e.g., inductors and common-mode chokes) in filter applications where the function of the component is to prevent the transmission of high-frequency current from a “noisy” port to a “quiet” port. We assume that the “quiet” port is shunted by a sufficiently low impedance (e.g., a capacitor) that it is effectively at ac ground, and that small amounts of high-frequency current into the “noisy” port are acceptable so long as they are not transmitted to the “quiet” port. These assumptions are satisfied in a wide range of filtering and power conversion applications. A test circuit for evaluating the attenuation performance of filters is illustrated in Fig. 2. The “noisy” port of the device under test is driven from the output of a network analyzer, and the response at the “quiet” port is measured at the 50  $\Omega$  input of the network analyzer.

The capacitance cancellation technique developed here is not geared towards changing the parasitic capacitance itself (e.g., the capacitance  $C_p$  of the device under test in Fig. 2). Rather, the deleterious effect of the parasitic capacitance - the current that passes through it at high frequencies - is nullified by a counterbalancing current injected at the quiet port. This counterbalancing current is injected by passive circuitry introduced expressly for this purpose. Referring to Fig. 2 (where an inductor and its parasitics form the device under test), the quiet port is assumed to be at ac ground, such that the voltage across the device under test is the ac components of the voltage at the noisy port. The parasitic capacitance current,  $i_p$ , injected into the quiet port by a noisy port voltage  $v_{ac}$  at the angular frequency  $\omega$  can thus be

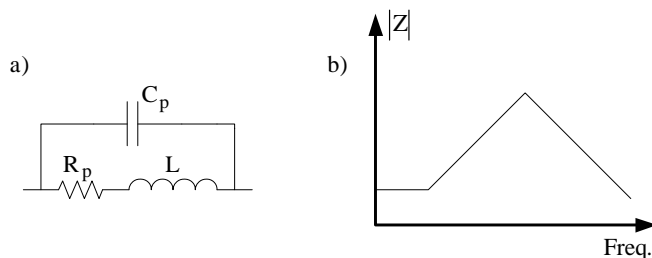


Fig. 1. A simple inductor model including parasitic effects. An impedance vs. frequency plot shows that the capacitance limits the impedance at high frequencies.

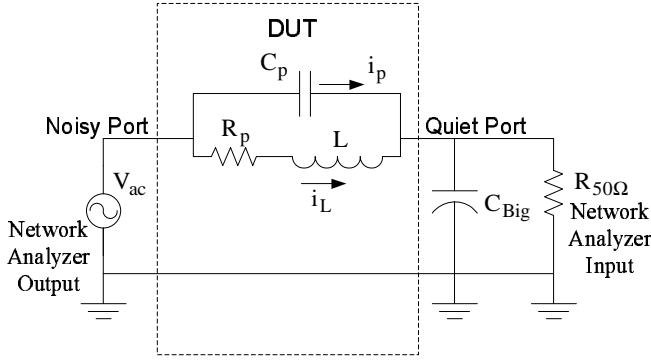


Fig. 2. A test circuit for evaluating the filtering performance of magnetic components. The device under test (DUT) is a filter inductor. The noisy port is driven by the output of a network analyzer. The quiet port is terminated by a capacitance and by the  $50\Omega$  input of the network analyzer.

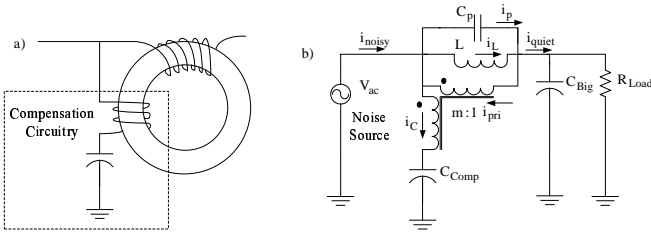


Fig. 3. (a) An additional winding and a capacitor are added to the inductor to form the circuit for parasitic capacitance cancellation. (b) As shown in the test circuit, the goal of the cancellation circuit is to null the circuit flowing through the parasitic capacitance.

expressed as:

$$i_p = j\omega v_{ac} C_p \quad (1)$$

The goal of cancelling the current  $i_p$  at the quiet port can be achieved by adding an additional compensation winding and capacitor to the inductor, as illustrated in Fig. 3a. The compensation winding only carries small, high-frequency currents, and can be implemented with very small wire. As shown in Fig. 3b, the compensation winding forms a transformer with the main winding, with the magnetizing inductance operating as the filter inductor. Neglecting other transformer parasitics (such as leakage) the circuit operation can be described as follows: The net current injected into the quiet port can be calculated as:

$$i_{quiet} = \frac{v_{ac}}{j\omega L} + j\omega v_{ac} [C_p - m(1-m)C_{comp}] \quad (2)$$

where  $m$  is the ratio of the compensating winding turns to the main winding turns, and  $C_{comp}$  is the value of the compensation capacitor. By selecting the winding ratio and compensation capacitor such that  $m(1-m)C_{comp} = C_p$ , the parasitic capacitance current injected into the quiet port is cancelled by the compensation circuit, leaving only the inductive current component.

While this technique eliminates the effect of the parasitic capacitance at the quiet port, it does not eliminate the parasitic effects in other regards. Most notably, the current into the noisy port actually increases at high frequencies. For any selection

of winding ratio and compensation capacitor described above, the currents  $i_p$  and  $i_{pri}$  will ideally cancel out and the current from the noise source will be  $i_L + i_C$  or

$$i_{noisy} = \frac{v_{ac}}{j\omega L} + j\omega v_{ac} C_p \frac{1}{m} \quad (3)$$

Since  $m$  is selected to be  $< 1$  to achieve cancellation at the quiet port, the capacitive current into the noisy port increases somewhat as compared to the uncanceled case. The additional current is the same as that of a small capacitor bypassing the noisy port. In many applications this is quite acceptable, and it becomes advantageous in filter applications where a capacitive bypass of the noisy port is desirable.

The proposed compensation technique is related to a number of other filtering and balancing techniques that have been explored in the past. The *topology* of the filter network that is created (e.g., Fig. 3b) is identical to coupled inductor filter structures that have been used widely for everything from notch-filtering [11], [12] to “zero ripple” filters [13]–[17] to filters incorporating parasitic inductance cancellation [18], [19]. However, the design goals and component values of these other circuit implementations are vastly different than the case considered here. The technique presented here bears closer relation to recent work on cancellation of common-mode noise in certain switching-power supply topologies [5]–[10]. These works utilize additional magnetics and capacitors to compensate common-mode currents injected through the capacitance from switching devices to the circuit ground or enclosure. The approach proposed here is different in that it focuses on parasitic capacitance appearing across magnetic components, and applies to a broad range of topologies and applications. Interestingly, these cancellation techniques are also related to the “neutralized” amplifier configuration developed more than fifty years ago, in which injected currents were used to compensate miller capacitance effects in vacuum tube audio amplifiers. [20], [21]. In this paper, we focus on the use of capacitance cancellation to enhance the performance of electrical filters. It is expected that the proposed approach will be less costly and burdensome to implement than more conventional EMI shielding techniques (e.g., a faraday shield) in many applications.

### III. EVALUATION

To validate the proposed approach, a number of prototype circuits have been constructed and tested. For simplicity, the prototypes circuits we describe here employ  $m = 0.5$  and  $C_{comp} = 4C_p$  except as otherwise specified. This turns ratio can be easily achieved with a 1:1 transformer in which one winding has a center-tapped connection. The effects of varying the turns ratio will also be examined.

A prototype filter circuit with capacitance cancellation was constructed using one half of a P3219-A common-mode choke (Coilcraft, Inc., Cary, IL). Only one winding of the choke was used in the testing; the other winding was left unconnected. The main winding of this toroidal choke comprises 45 turns of 25 gauge wire in a single layer, forming a 10.8 mH filter inductance, with approximately 16 pF of parasitic capacitance. A compensation winding of 22 turns of gauge 30 wire was added to the choke, as illustrated in Fig. 3a. A range of

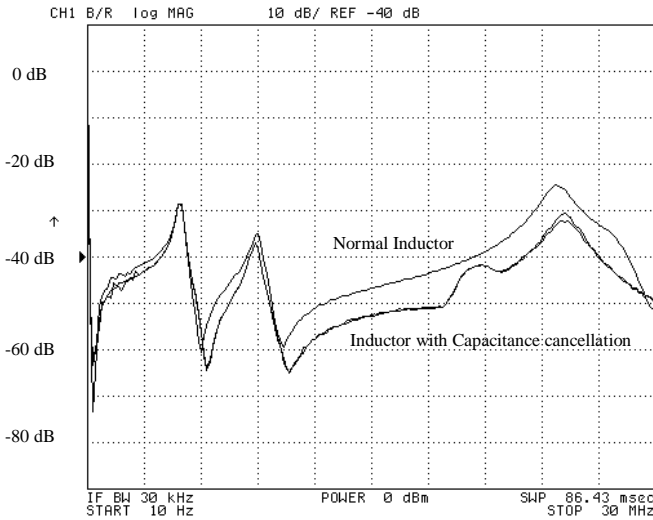


Fig. 4. Ratio of input to output voltage for the P3219-A Coilcraft choke. The higher curve is the response without the capacitance cancellation. Above 10 MHz there is about 7 dB of improvement from using the capacitance reduction technique.

compensation capacitor values were tested to identify the best value and an 18 pF ceramic capacitor was selected. A 3.3 nF ceramic capacitor was used to bypass the quiet port.

The filter circuit was evaluated using the network analyzer-based test setup illustrated in Fig. 2. The filter circuit is driven from the network analyzer output, and the response at the quiet port is measured at the 50  $\Omega$  input of the network analyzer. Figure 4 shows the magnitude of the transfer function from the the noisy port to the quiet port over the conducted EMI frequency range (up to 30 MHz) both with and without parasitic capacitance cancellation. As can be seen, the proposed cancellation technique improves performance by approximately 7 dB in the frequency range of 10 MHz to 28 MHz; tests on other devices provided similar results - a 5-10 dB improvement in performance at high frequencies. Most of the irregular peaks in the Figure are due to unmodelled, higher frequency parasitics in the filter.

While the proposed cancellation technique does improve filter performance, the results are not as good as might be expected. The main source of this limitation is the leakage inductance of the cancellation transformer. All impedances in series with the compensation capacitor, especially the leakage inductance, will compromise the high frequency performance of the cancellation. Treating the leakage inductance of the compensation winding as part of a compensation impedance  $Z_C$  and ignoring the primary side leakage inductance, the quiet port current becomes

$$i_{quiet} = \frac{v_{ac}}{j\omega L} + j\omega v_{ac} C_p - \frac{m(1-m)}{Z_{comp}(j\omega)} \quad (4)$$

$$i_{quiet} = \frac{v_{ac}}{j\omega L} + v_{ac} \frac{C_p C_C L_C (j\omega)^3}{C_C L_C (j\omega)^2 + 1} \quad (5)$$

where  $L_C$  is the secondary leakage inductance in series with  $C_C$ . The term  $C_C L_C (j\omega)^2$  greatly affects the performance of capacitance cancellation.  $C_C$  is minimized when the turns

ratio,  $m$ , is 1/2 and  $L_C$  is dependant on the magnetic element and is lower for transformers with a lower turns ratio. Thus the coupling coefficient of the primary and cancellation windings is a critical factor in achieving good cancellation performance.

The transformer used in Fig. 4 was rewound such that the secondary has three turns, resulting in a turns ratio of 0.06. The compensation capacitor was chosen to maximize the impedance of the inductor at frequencies lower than 6 MHz, the best compensation capacitors were experimentally determined to be 56 pF and 59 pF when the turns ratios are 0.5 and 0.06. Note that 56 pF is much larger than the expected compensating capacitor for a turns ratio of 0.5. However, this capacitance, when considered with the leakage inductance in the compensation branch, leads to the system with the best performance at the frequencies of interest. Assuming that the the transformer with 10.8 mH primary inductance has a coupling coefficient is 0.98 in both cases, the value of  $C_C L_C$  changes from  $3.024 \cdot 10^{-15} HF$  to  $3.81 \cdot 10^{-17} HF$  when the turns ratio changes from .5 to .06. A comparison of the performance of the two cases of capacitance cancellation is shown in Fig. 5. This figure shows that the system with the lower turns ratio outperforms the other system at frequencies below 6 MHz, and using a lower turns ratio will raise the self-resonant frequency from 400 kHz to 1.4 MHz.

In order to quantitatively evaluate the effects of the coupling coefficient on performance, a PSpice model of the experimental system leading to Fig. 4 was created (without the higher order parasitics). The parasitic capacitance of the inductor was set to 15 pF and the coupling coefficient was varied between .98 and 1. The simulated filter attenuation at 20 MHz is plotted as a function of the coupling coefficient in Fig. 6. This figure shows that the effectiveness of capacitance cancellation is very sensitive to the coupling coefficient. These insights are also relevant to other passive EMI cancellation techniques, such as those in [5]–[8].

This test was expanded to take into consideration changes in the turns ratio and changes in the amount of inductance and capacitance of the inductor under test. Fig. 7 shows a normalized plot of the filter attenuation at 20 MHz as a function of the term  $C_C L_C$ . Each line on the plot shows a set of simulations with different leakage inductances with a unique turns ratio, magnetizing inductance, and parasitic capacitance. Since some of the systems have different parasitic capacitances the total amount of possible attenuation improvement will be different, thus for each set of simulations the amount of attenuation is given as a percentage of the maximum possible case (15 to 30 dB depending on the case). The three outlying lines represent cases in which the turns ratio is 0.875, otherwise a clear relationship exists between the relative improvement in attenuation and the term  $C_C L_C$ . The data used to generate this plot shows that as the turns ratio,  $m$ , decreases, the range of the transformers coupling coefficients over which beneficial results occur will increase. Hence, transformers with lower coupling coefficients benefit from a low turns ratio. The higher lines in the figure, though, correspond to systems with high turns ratios and high coupling coefficients, thus a transformer with near ideal coupling will lead to the overall best system possible.

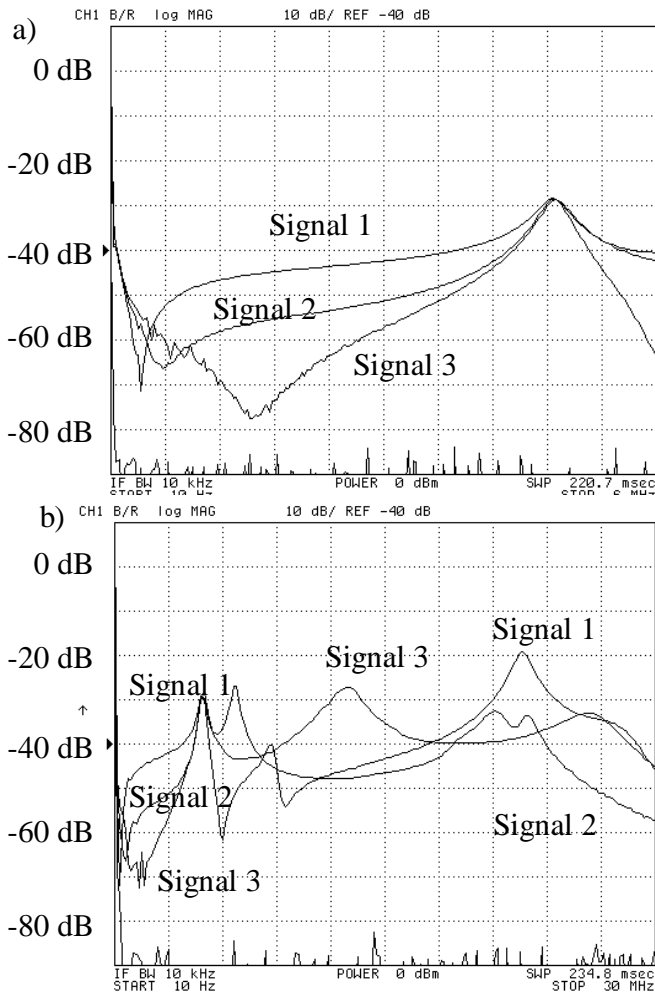


Fig. 5. Ratio of output to input voltage for the P3219-A Coilcraft choke in which the turns ratio of the transformer is changed from 0.5 to 0.06. The compensation capacitors were chosen in both cases to improve performance below 6 MHz. Figure a) shows this frequency range. Signal 1 is the result of the normal inductor and signal 2 is the result of the inductor with capacitance cancellation with a turns ratio of 0.5 and a compensation capacitor of 56 pF. The system is changed such that the turns ratio is 0.06 and the compensation capacitor is 59 pF and the performance is improved to signal 3. Figure b) shows that above 6 MHz the performances of all three systems are dominated by other parasitics and that each system will outperform the others over some frequency range.

IV. ALTERNATIVE IMPLEMENTATION

Here we introduce an alternative implementation of the capacitance cancellation technique that avoids the magnetic coupling limitations of the simple implementation. Rather than relying on the limited magnetic coupling achievable with an additional winding on the filter inductor, the alternative implementation achieves the cancellation using a separate radio-frequency (RF) transformer in parallel with the filter inductor, as illustrated in Fig. 8. The compensation capacitor is selected to compensate the parasitic capacitances of both the transformer and inductor. As will be shown, this technique can achieve highly effective capacitance cancellation using only small, inexpensive components.

The tradeoffs that arise in designing the induc-

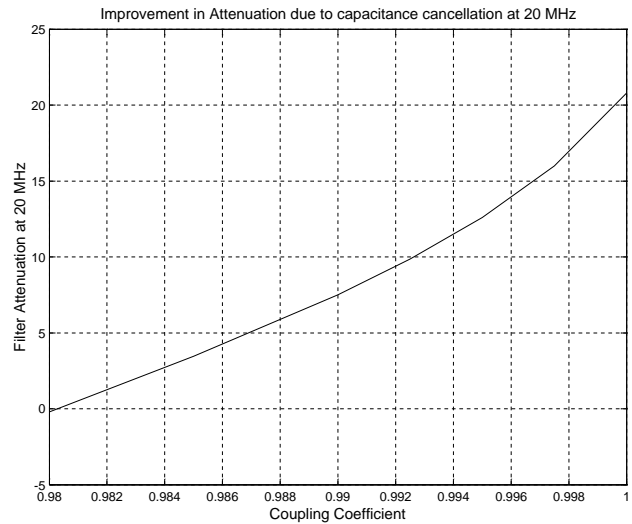


Fig. 6. The effects of changing the coupling coefficient on the system in Fig. 2. The parasitic capacitance of the inductor is 15 pF, the magnetizing inductance is 50  $\mu$ H, and the turns ratio ( $m$ ) is 0.5.

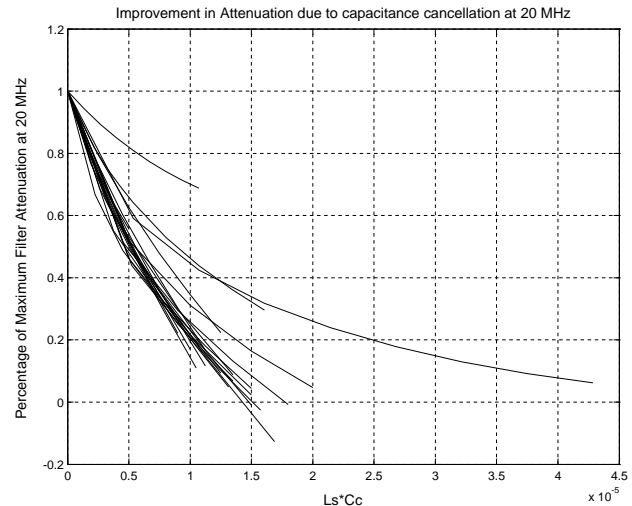


Fig. 7. The effects of changing the term  $C_C L_C$ , the total series capacitance and inductance in the compensation path, on the improvement of attenuation at 20 MHz. Each line corresponds to a specific magnetizing inductance, parasitic capacitance and turns ratio of the transformer.

tor/transformer combination are similar to those that occur in some types of active EMI filters [22]. These design tradeoffs are summarized here. First, the RF transformer should have a high coupling coefficient to enable good capacitance cancellation to be achieved. The transformer magnetizing inductance should be similar to or larger than the original filter inductance to realize the desired filtering performance because it is desirable to have the majority of the current going through the original filter. Since it only needs to carry the small cancellation currents, the RF transformer can be wound with very fine wire, and can be made quite small and inexpensive. Differences in winding resistances between the RF transformer and filter inductor can be used to ensure that low-frequency currents flow through the filter inductor,

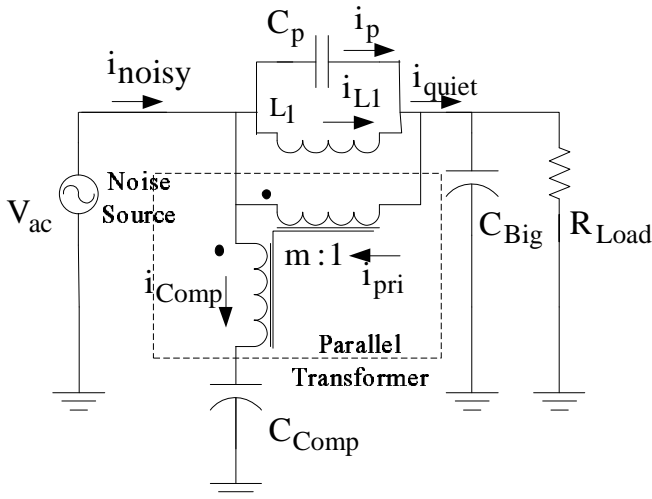


Fig. 8. Capacitance cancellation using a parallel RF transformer to inject cancellation currents.

though a small blocking capacitor could also be introduced for this purpose. One RF transformer meeting these criteria is the WB3010-1 (Coilcraft, Cary, IL). This center-tapped transformer has a magnetizing inductances of 760  $\mu\text{H}$  and a coupling coefficient exceeding 0.999 in a six-pin DIP package. Because the transformer is center-tapped, a 2:1 transformer is easily created, making this design suitable for capacitance cancellation applications.

The system shown in Fig. 8 was tested in the test setup of Fig. 2. The filter inductor is one half of a 1 mH common-mode choke constructed with 12 turns fully packed on an ungapped RM12 core. The 1 mH inductor, developed for automotive filtering applications, has approximately 20 pF of parasitic capacitance. The quiet-port bypass capacitance comprises the parallel combination of a 10  $\mu\text{F}$  tantalum capacitor and a 1  $\mu\text{F}$  ceramic capacitor. The transformer in parallel with the inductor is the WB3010-1, and an 86 pF ceramic capacitor is used. Experimental results for this prototype system are shown in Fig. 9. The highest curve shows the performance without the compensation circuit. The middle trace shows the performance with the capacitance cancellation. The lowest curve shows the noise floor of the network analyzer (the measured response with the test circuit disconnected). Capacitive cancellation improves the attenuation by 25 dB at 30 MHz.

Capacitance cancellation was also applied to improve the common mode performance of an EMI filter. A commercial EMI line filter, the Schaffner FN2010-6-06, is used to test capacitance cancellation. The filter is a one stage filter and is shown in Fig. 10. The parasitic capacitance, as measured across either both positive or negative terminals, is 31 pF. A small center-tapped transformer, EPC3115-7 from PCA Electronics Inc., is added outside the filter case. This transformer has a turns ratio of 1:1.5, so the secondary is connected across the filter and the primary is used for the compensation path. A variety of compensation capacitors were experimentally tested and a ceramic 100 pF capacitor was chosen. This capacitor is connected from the center-tap of the transformer primary

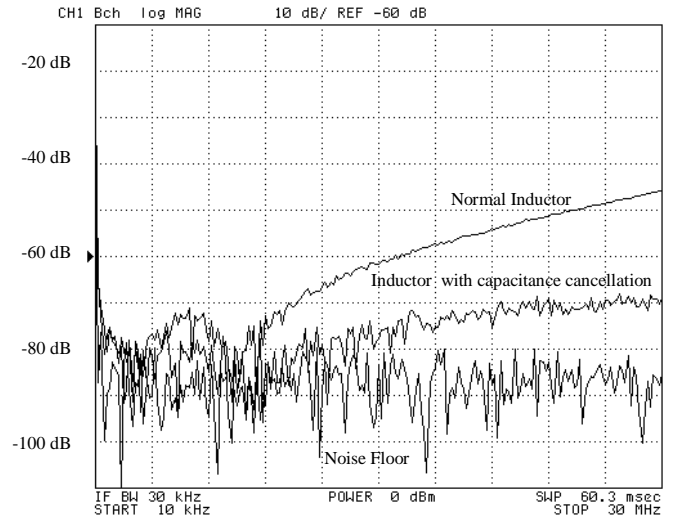


Fig. 9. Performance of a filter inductor with and without capacitance cancellation. The inductor ( $L_1$ ) is a packed RM12 core with 1 mH of inductance and the cancellation transformer is a Coilcraft WB3010-1.

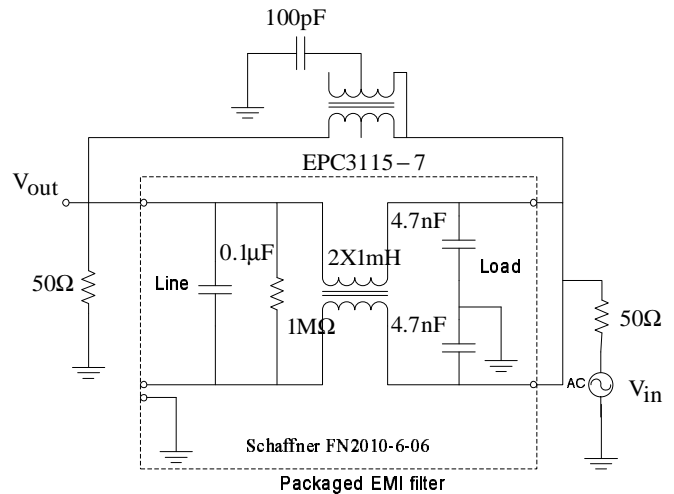


Fig. 10. The schematic for the common mode choke with capacitance cancellation and setup for a CM test. The two added elements are located on the case of the filter. A common mode signal is introduced from the load side of the filter and the common mode noise is measured on the line side of the filter.

to the ground (i.e. the enclosure). The modified circuit and the common mode test setup are shown in Fig. 10. The resulting circuit has better performance at high frequencies. The parasitic capacitance of the filter choke is the dominant limit to attenuation at frequencies over 1 MHz until the self resonance of the Y-capacitors (The capacitors from either line to ground) at 23 MHz. In this range of frequencies, the filter with parasitic capacitance cancellation has better performance. An improvement of at least 10 dB in attenuation is achieved from 3 to 20 MHz and an improvement of 20 dB is achieved at 14 MHz. Results of this test are shown in Fig. 11.

V. CONCLUSIONS

This paper introduces a technique for improving the high-frequency performance of filter inductors and common-mode

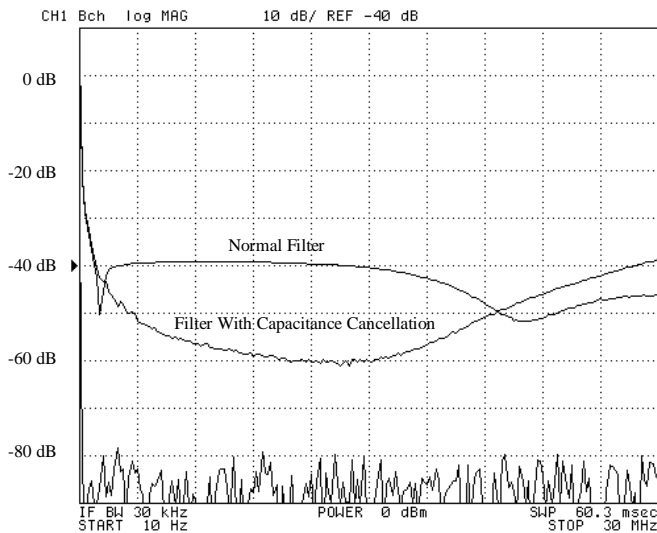


Fig. 11. A plot comparing the performance of the common mode response of an EMI filter, Schaffner FN2010-6-06, and one modified with capacitance cancellation.

chokes by cancelling out the effects of parasitic capacitance. This technique uses additional passive components to inject a compensation current that cancels the current flowing through the inductor parasitic capacitance, thereby improving high-frequency filtering performance. Two implementation approaches for this technique are introduced. The first implementation achieves cancellation using an additional small winding on the filter inductor and a small capacitor. This approach is effective where very high coupling of the windings can be achieved or where only moderate performance improvements are required. The second implementation utilizes a small RF transformer in parallel with the filter inductor to inject cancellation currents from the compensation capacitor. This technique requires an additional component (the transformer), but can provide a high degree of cancellation. Experimental results confirm the theory in both implementations and the application of this technique to a common mode EMI filter.

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