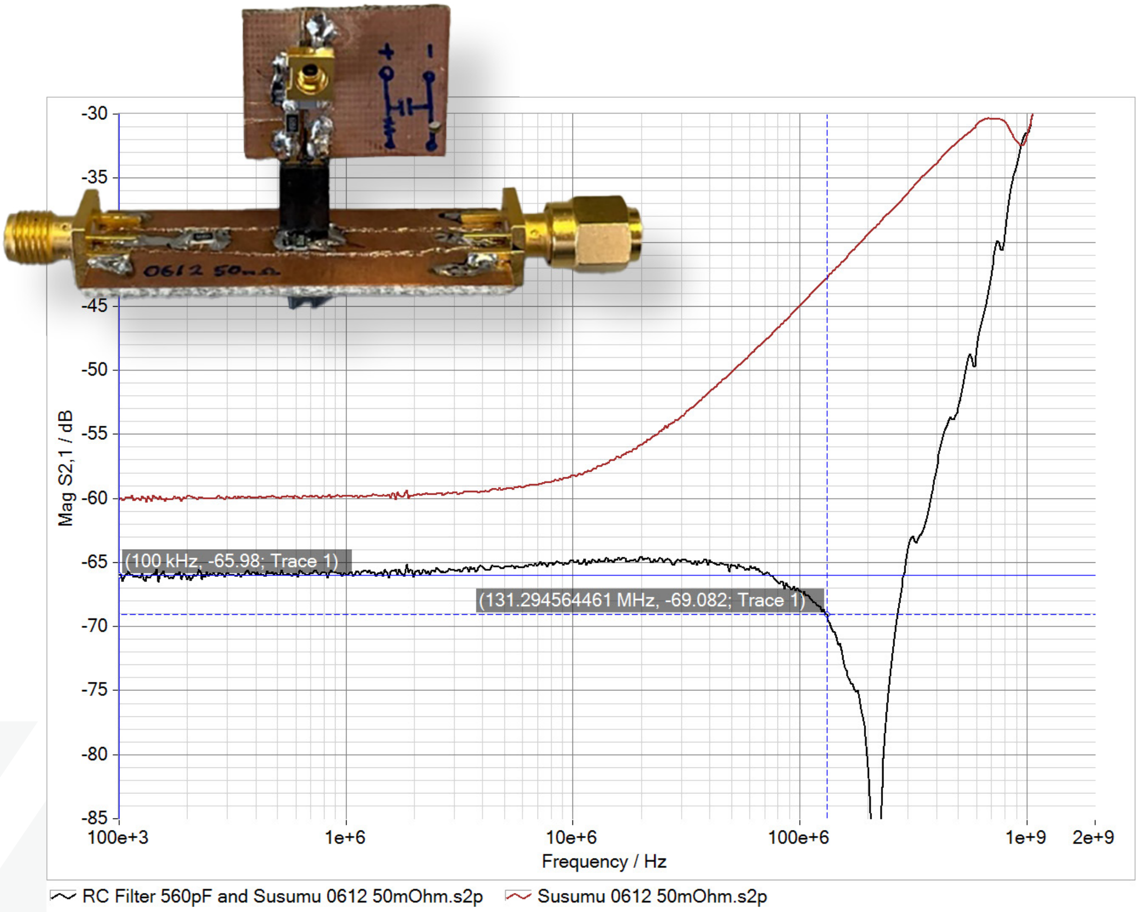
# Compensating for Series Inductance in Shunt Resistors for High Frequency Measurements

Seamus Brokaw, Applications Engineer

WHITE PAPER



## Abstract

SMD resistors and off-the-shelf current viewing resistors (CVRs) can introduce parasitic inductance that causes ringing and exaggerated peaks. This paper describes a technique for defining a simple RC filter to enable shunt-based current measurements beyond 1 MHz.

VNA measurements are used to determine the frequency response of a physical shunt. Time domain measurements show the impact of the parasitic inductance.

The shunt is then modeled as a series RL circuit and an RC filter is added to the simulation to flatten the response. The RC filter is applied and measured to show improvements in both the frequency domain (VNA) and time domain (oscilloscope).


## Introduction

When it comes to accurate current measurements, traditional methods like current transformers (CTs) and current clamp probes are often the first choice. However, these methods have limitations, especially when trying to capture high-frequency signals or fast transients. CTs and current clamps tend to introduce errors such as phase shift, signal attenuation, and bandwidth limitations, making them less suitable for precise measurements in the MHz range.

Current shunts offer a direct measurement approach by converting the current to a voltage using a low-resistance element. Unlike CTs and Hall-effect sensors, shunts are unaffected by magnetic interference or external fields, which makes them reliable in environments with high electromagnetic noise. Additionally, shunts offer a broader frequency response compared to CTs, which can suffer from saturation effects and limited low-frequency performance. Shunts also have a compact design, are less expensive, and typically introduce minimal phase error, making them particularly suitable for applications where precise, high-bandwidth current sensing is essential.

However, off-the-shelf SMD resistors and commercially available CVRs come with their own challenges, primarily due to parasitic inductance. This inductance can introduce ringing, exaggerated peaks, and inaccurate results, particularly beyond 1 MHz.

To overcome these issues and achieve accurate measurements in the 1 MHz to 100 MHz range, new techniques of compensation and probing are required. By properly addressing parasitic effects, current shunts can provide better fidelity in high-frequency environments, making them a superior choice for applications demanding precision beyond the capabilities of conventional current measurement methods. New probing methods like the TICP Series Isolated Current Probe are ideally suited for current shunt measurements. Its low noise architecture and isolated design allows for over 1000 V common mode voltage rating and over 140 dB common mode rejection ratio (CMRR) all while measuring from µA currents up to kA currents.

## Parasitic Series Inductance in Resistors

Parasitic series inductance in surface mount resistors arises from the physical layout and construction of the resistor, causing it to act like an inductor at higher frequencies. This inductance is influenced by factors such as the resistive material, where thin-film or metal foil designs generally have lower inductance than thick-film or wire-wound designs. The geometry and size of the resistor also play a role, with larger packages and longer current paths increasing inductance. The internal layout, including termination lengths and spacing between terminals, further affects the inductive value, which can significantly impact performance in high-frequency circuits.

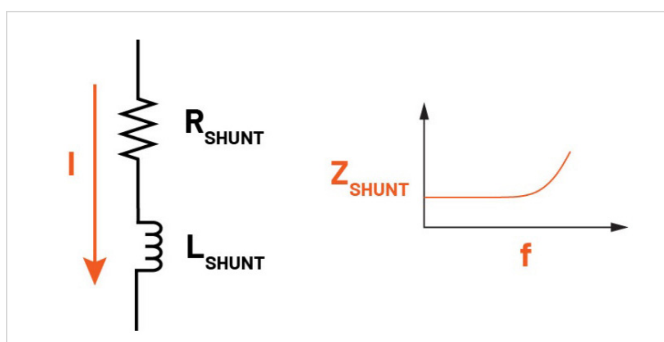



**Figure 1. Especially with low-value shunt resistors, parasitic inductance will begin to impact the overall shunt impedance at frequencies above 1 MHz.**

The corner frequency occurs at the -3 dB point where the magnitude of the transfer function H(ω) equals $1/\sqrt{2}$. From this point on, the impedance of the parasitic inductance dominates the shunt impedance and the nominal resistance of the shunt becomes irrelevant.

$$H(\omega) = \frac{R_S}{(Rs + j\omega L_S)}$$

$$|H(\omega)| = \frac{1}{\sqrt{2}}$$

$$\omega_0 = \frac{R_S}{L_S}$$

$$f_C = \frac{R_S}{2\pi L_S}$$

Examining the equation, we can see that the useful frequency band becomes lower with smaller values of Rs and also drops with increasing parasitic inductance values. Thus, for a flat frequency response, it's best to start with the largest shunt resistor value your circuit can tolerate and do everything possible to minimize shunt inductance.

Inductance can be lowered through careful selection of resistor material, selecting package sizes that are "wide and short" such as the 0612 package shunt used here. Another method for managing parasitic inductance is to place several shunts in parallel and measure voltage across the parallel combination, since inductors placed in parallel reduce the combined total inductance.

## How Measurements are Affected

In this example, a 50 mΩ, 1 W resistor in an 0612 package (Susumu PRL1632-R050-F-T1) is mounted on a fixture and a VNA is used to measure the frequency performance.

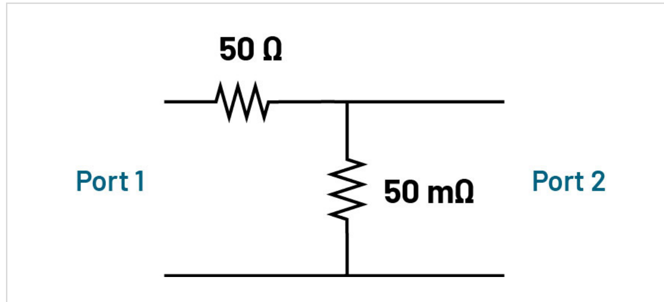



**Figure 1. A simple shunt resistor circuit configured for an S21 measurement on a vector network analyzer (VNA).**

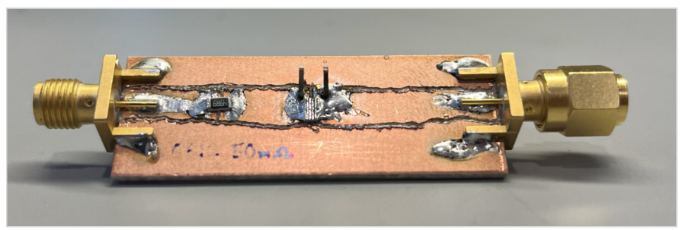


**Figure 2. The circuit from Figure 1 with a 50 mΩ thin film shunt resistor, in an 0612 package mounted on a fixture. Port 2 is across the square pins tied to the shunt resistor in the center of the PCB.**

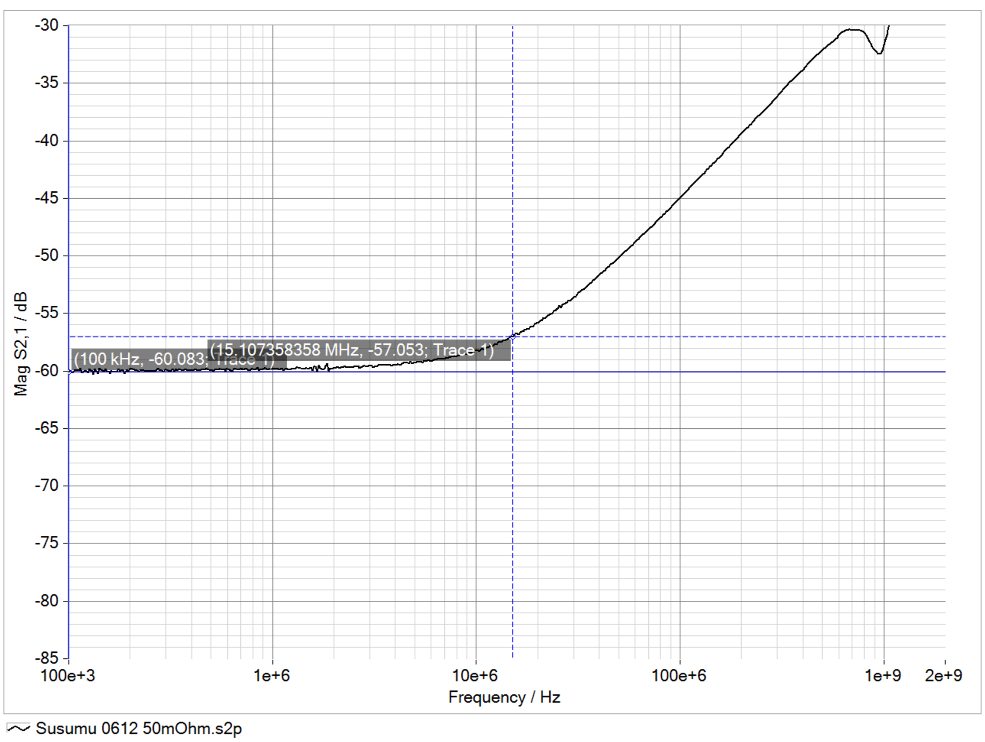



**Figure 3. VNA measurement (S21) of shunt resistor in Figure 1. Corner frequency of 15.1 MHz is indicated by the cursor.**

The S21 plot from the VNA shows the corner frequency (+3 dB point) at 15.1 MHz. With this shunt by itself, any measurements above 15.1 MHz will be incorrectly amplified and exaggerated. This will affect peak current measurements on every edge and make accurate power calculations impossible on fast edges.

**Figure 4** shows time-domain data, comparing the step response of a passive probe straight out of the generator with the same step passed through the 50 mΩ shunt. The edge is greatly exaggerated. The passive probe step response represents a control since its construction makes a finely tuned and flat frequency response measurement system. This is in contrast to the uncompensated shunt resistor's extreme overshoot.

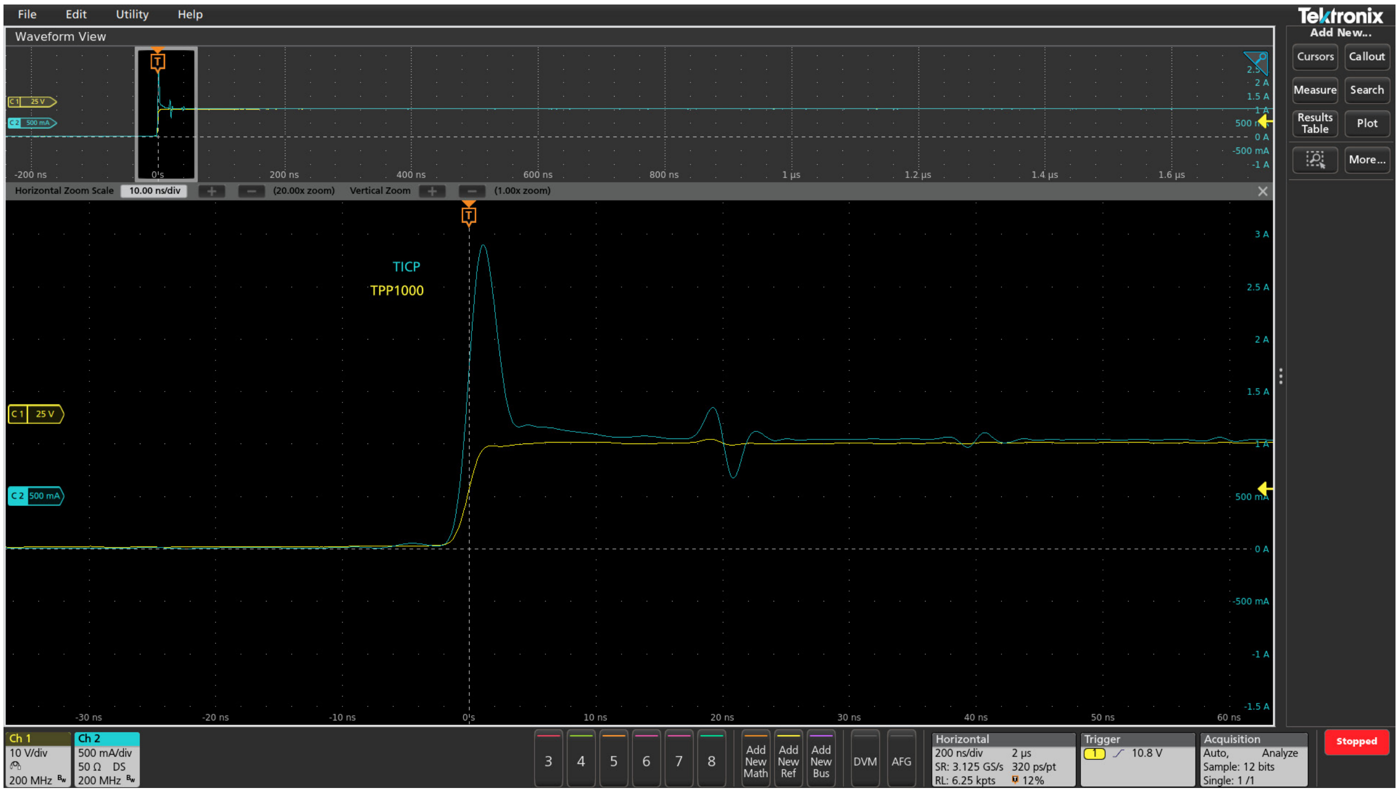
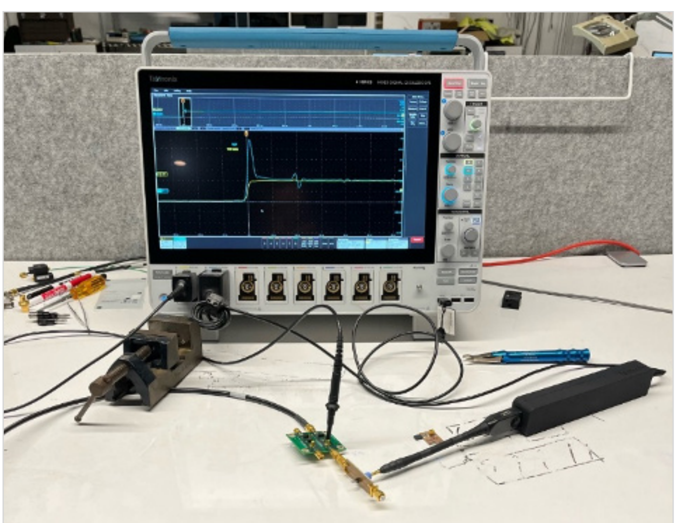



**Figure 4. Measurements of edges from a fast step generator. The yellow trace is measured using a 1 GHz passive probe connected directly to the generator output. The blue trace is from a current shunt probe measuring across the 50 mΩ shunt resistor, which is connected to the same generator output.**



The current shunt probe being used in this example is a Tektronix TICP Series IsoVu Isolated Current Shunt Probe. To measure the signal off a shunt, a low-noise isolated probe like TICP is ideal. Isolation allows for the shunt to be placed anywhere in the circuit, even on a 1800 V voltage rail. And the low noise architecture provides a greater sensitivity than any high impedance probe. The probe faithfully measures the overshoot from the shunt in this example.

**(Left) Figure 5. Test setup used to generate measurements in Figure 4. A TPP1000 1 GHz 10x passive probe is connected via a breakout board to the output of the step generator which feeds into the shunt resistor fixture. A TICP100 isolated current shunt probe is connected across the shunt.**

## Simulating the Inductance of the Shunt and the RC Filter

With the 15.1 MHz corner frequency obtained on the VNA, the shunt's equivalent inductance and a matching single pole RC filter can be created to counteract the zero contributed by the parasitic inductor. Using a circuit simulation tool, the effective series inductance (ESL) value is varied until the corner frequency matches the results from a VNA.

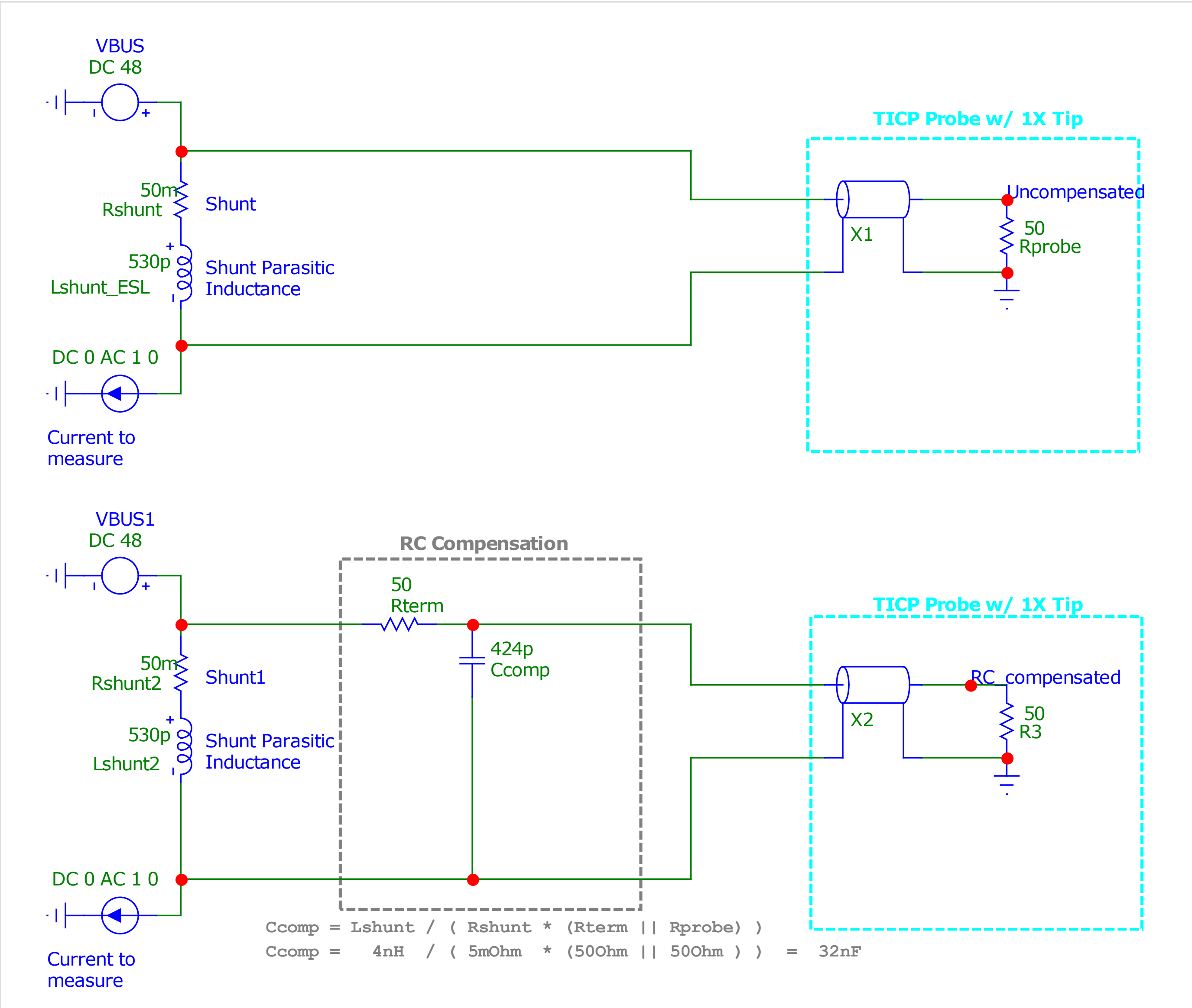



**Figure 5. In the upper model iterative estimates of ESL are plugged in until the 15.1 MHz corner frequency is duplicated in the AC simulation. In the lower model, an RC filter with R=50 Ω is inserted into the circuit to counteract the parasitic inductance in the shunt. The results of these two simulations are shown in Figure 5.**

Once the simulation data matches what the real-world VNA shows, an appropriate RC filter is simulated to flatten out the combined response, as shown in the lower portion of **Figure 5**. The capacitance value can be found by varying the Ccomp value until the resulting frequency performance is flat. The resulting RC filter simulation will be used to make a real-world filter and then the performance of this combination can be checked again on the VNA and with a time-domain step-response on the oscilloscope.

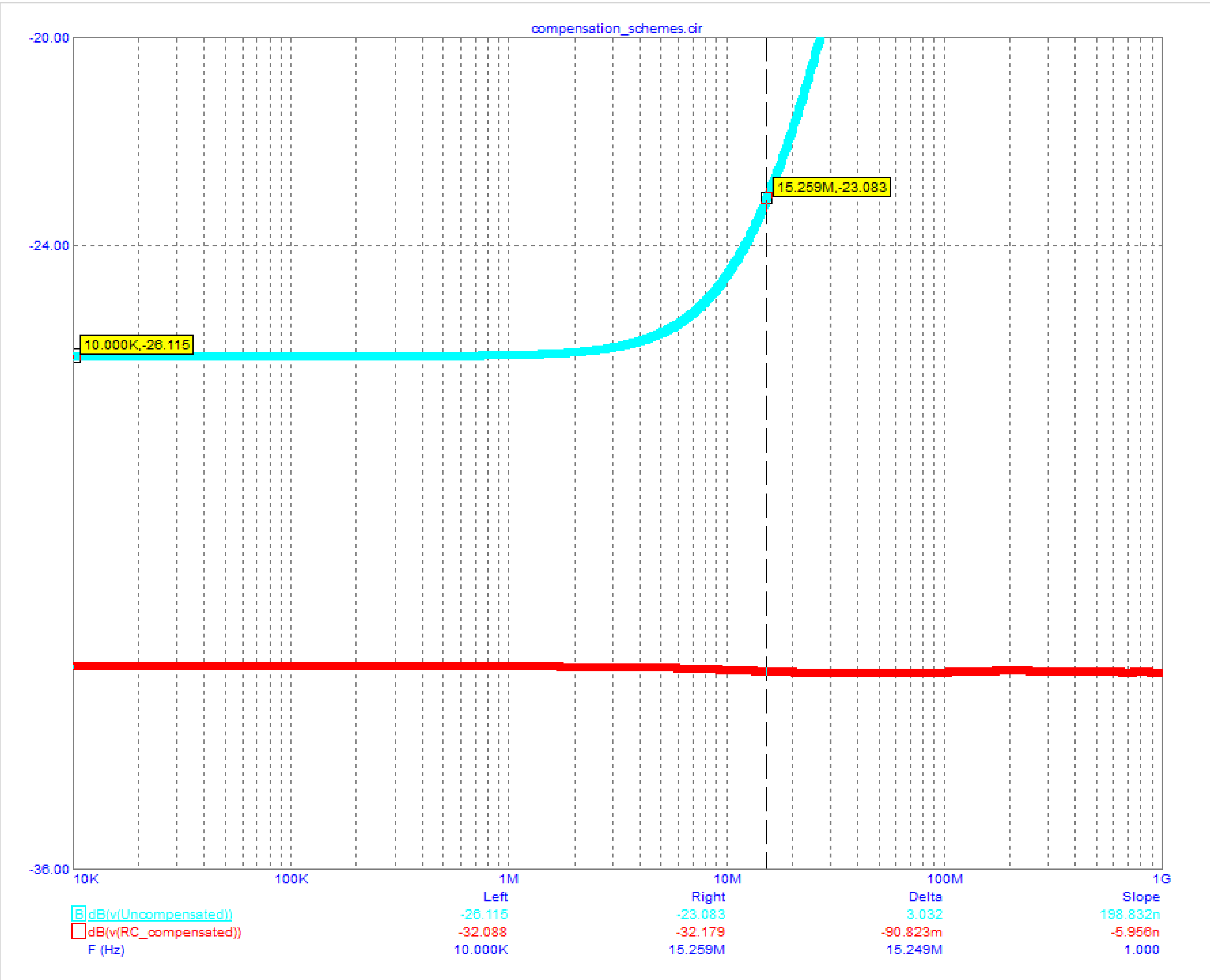



**Figure 6. The upper, blue trace shows the response of the uncompensated shunt to an AC analysis, with a corner frequency of 15.3 MHz. The lower trace shows the much flatter response of the same circuit with an added RC filter.**

These simulations predict that a 547 pF capacitor will significantly flatten out the inductive kick. Next, that RC filter will be constructed, and the performance of the combination will be confirmed with real-world data.

## RC filter for Compensating Inductive Effects

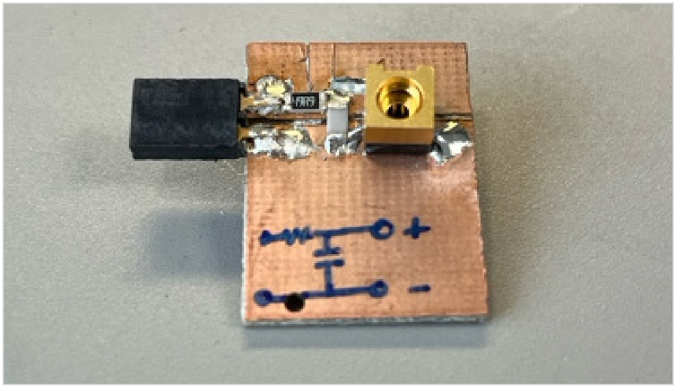



Figure 7. A low-pass RC filter, with R=50 Ω and C=547 pF, based on the results of simulations.

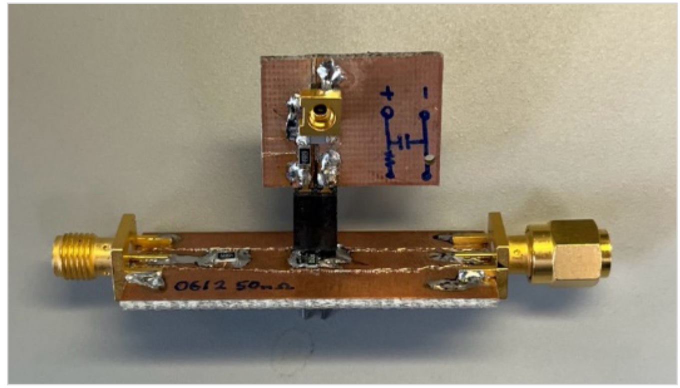



Figure 8. Shunt fixture with low-pass RC filter installed.

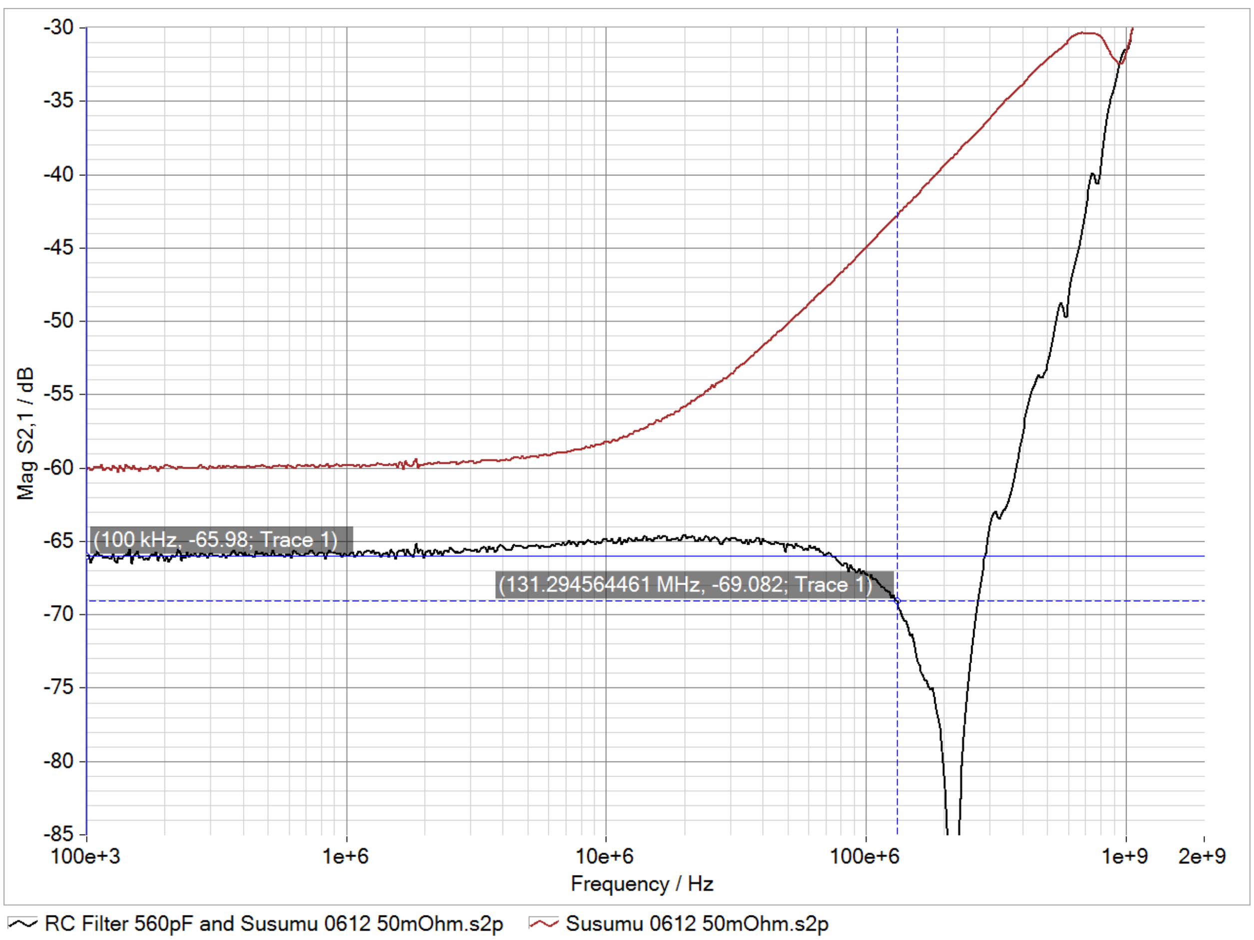



Figure 9. The upper (red) trace represents the frequency response of the uncompensated shunt resistor. The lower (black) trace represents the frequency response of the combined network with RC compensation.

From the VNA data with this RC filter board, the corner frequency (-3 dB) is improved from 15 MHz to over 130 MHz. That is more than an 8× improvement in bandwidth from a simple, single pole filter.

The time domain information shows a similar story, with the high frequency edge much more closely matching the passive probe step response. Again, a passive probe is used here to show a measurement system that is close to ideal and useful for comparison.

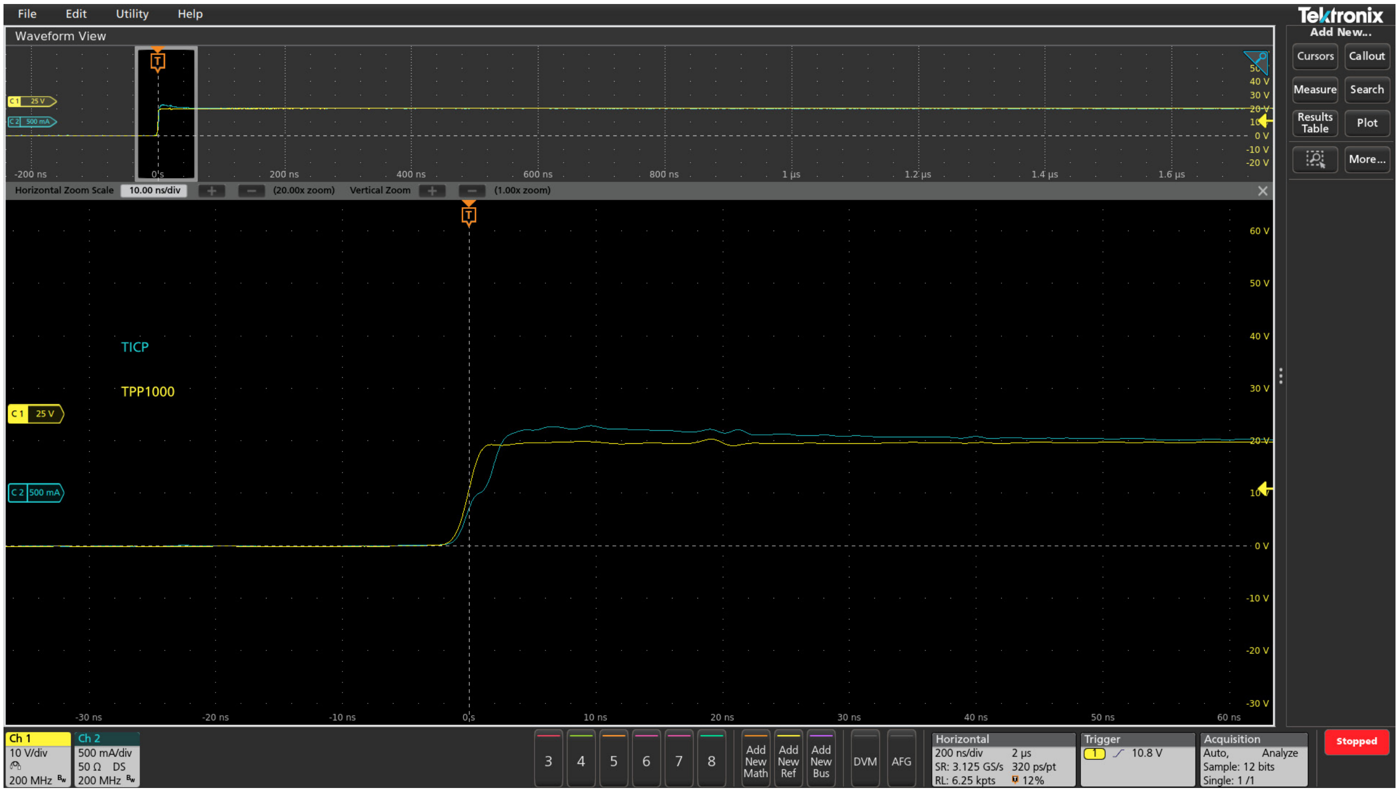
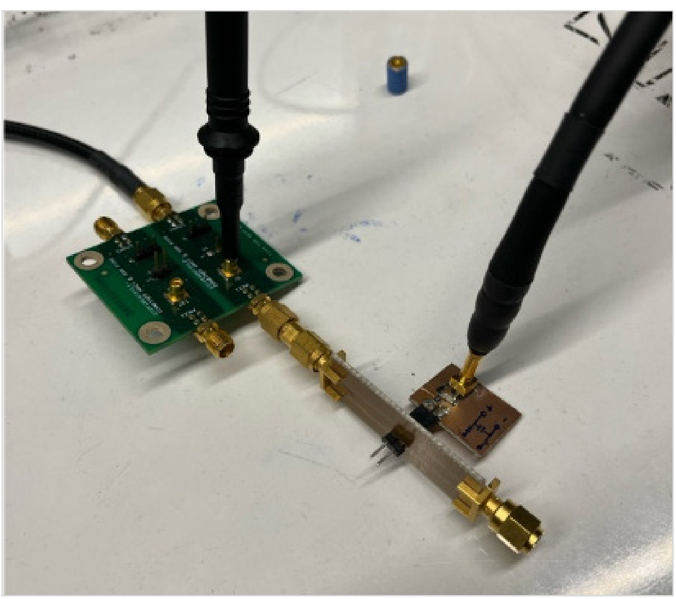



**Figure 10. Measurements of edges from a fast step generator, similar to Figure 4 but with an low-pass RC filter applied across the shunt. The yellow trace is measured using a 1 GHz passive probe connected directly to the generator output. The blue trace is from a current shunt probe measuring across the 50 mΩ shunt with a low-pass filter installed (R=50 Ω and C=547 pF).**



Further improvements are possible with multi-pole designs and more accurate modeling of shunt behavior. As you may expect, the filter boards themselves have their own parasitic elements that also must be compensated, in an infinite loop of diminishing returns. The parasitic elements can be seen in the VNA data above 280 MHz where the shunt plus filter response returns to being strongly inductive.

**(Left) Figure 11. Probing for the measurements in Figure 10. The TPP1000 (left) shows the output of the step generator. The TICP100 isolated current shunt probe is connected across the capacitor of the low-pass filter, which has been connected across the shunt resistor.**

## Conclusion

Without compensation, shunt resistors will exaggerate high frequency signals and lead to false peak current readings and excessive overshoot. 20 MHz bandwidth filters can cut out the worst of this response but to get current readings out to 100 MHz and beyond, a compensating filter must be used.

Current shunts provide a straightforward, direct measurement by converting current to voltage across a low-resistance element. Unlike CTs and Hall-effect sensors, shunts are immune to magnetic interference and external fields, offering dependable performance in high electromagnetic noise environments. They also deliver a wider frequency response than CTs, which can be limited by saturation and low bandwidth specifications. With their compact design, lower cost, and minimal phase error, shunts are especially suited for applications requiring precise, high-bandwidth current sensing.

## Contact Information:


**Australia** 1 800 709 465

**Austria*** 00800 2255 4835

**Balkans, Israel, South Africa and other ISE Countries** +41 52 675 3777

**Belgium*** 00800 2255 4835

**Brazil** +55 (11) 3530-8901

**Canada** 1 800 833 9200

**Central East Europe / Baltics** +41 52 675 3777

**Central Europe / Greece** +41 52 675 3777

**Denmark** +45 80 88 1401

**Finland** +41 52 675 3777

**France*** 00800 2255 4835

**Germany*** 00800 2255 4835

**Hong Kong** 400 820 5835

**India** 000 800 650 1835

**Indonesia** 007 803 601 5249

**Italy** 00800 2255 4835

**Japan** 81 (3) 6714 3086

**Luxembourg** +41 52 675 3777

**Malaysia** 1 800 22 55835

**Mexico, Central/South America and Caribbean** 52 (55) 88 69 35 25

**Middle East, Asia, and North Africa** +41 52 675 3777

**The Netherlands*** 00800 2255 4835

**New Zealand** 0800 800 238

**Norway** 800 16098

**People's Republic of China** 400 820 5835

**Philippines** 1 800 1601 0077

**Poland** +41 52 675 3777

**Portugal** 80 08 12370

**Republic of Korea** +82 2 565 1455

**Russia / CIS** +7 (495) 6647564

**Singapore** 800 6011 473

**South Africa** +41 52 675 3777

**Spain*** 00800 2255 4835

**Sweden*** 00800 2255 4835

**Switzerland*** 00800 2255 4835

**Taiwan** 886 (2) 2656 6688

**Thailand** 1 800 011 931

**United Kingdom / Ireland*** 00800 2255 4835

**USA** 1 800 833 9200

**Vietnam** 12060128

* European toll-free number. If not accessible, call: +41 52 675 3777



Rev. 02.2022


Find more valuable resources at [TEK.COM](https://www.tek.com)




041125 SBG 51W-74140-1