A broadband filter proves itself in multiple dielectrics

A unique passive component design improves the filtering performance of ferrites.

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INTRODUCTION

TODAY, AS MORE STRINGENT EMC REGULATIONS proliferate throughout the world, effective filtering from DC to GHz frequencies has become increasingly more difficult using current filter components. Gone are the days when a narrow band filter could meet compliance. We now live in a world with BlueTooth®, digital cell phones and optical networks to the home. Computers with GHz microprocessors have now become the norm. Even automakers have stepped in with their own EMC requirements beyond 1 GHz as passenger compartments offer an array of sophisticated electronics. Standard passive components used for filtering and immunity protection have not kept pace with new technology and are nearing their limitations in filter performance.

Presently, multiple passive components are combined to form networks for effective broadband filtering up to 1GHz (Figure 1).

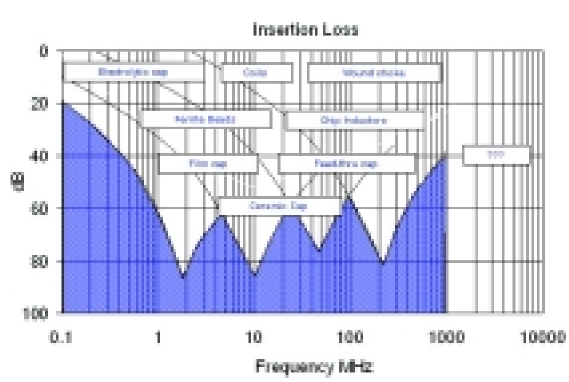


Figure 1. Components used in combination for filtering.

As circuit designers look for new ways to attenuate noise in order to meet radiated and conducted emissions requirements from kHz on up, filter networks have increased in complexity and size, using up more and more board real estate.

One option for reducing performance pressures on standard filter components is to design quieter circuits through careful EMC design. Increased attention to trace routings, module location, board layers, and proper grounding can go a long way toward EMC compliance. Differential signaling for high-speed applications offers a quieter circuit through magnetic flux cancellation. However, any imbalance at megabit or gigabit speeds is detrimental to data transfer and can cause errors, and, at the same time, it gives rise to radiated emissions if tight tolerance filtering is not applied. This article seeks to introduce a simple solution to broadband filtering that uses fewer passive components. The design shown that makes minimal structural changes to presently used multi-layer passive component technology but yields highly effective filtering results. Further, it will be shown through data that this unique patented design enhances the capability of the dielectric medium in which it is manufactured.

COMMON- AND DIFFERENTIAL-MODE FILTERING

Common-mode noise (longitudinal) is the noise voltage which appears equally and in phase from each signal conductor to ground.[1] Differential-mode noise is the noise that causes the potential of one side of the signal transmission path to be changed relative to the other side.[1]

Common-mode and differential-mode noise is present in nearly every circuit from low-voltage AC or DC power lines to high-speed digital circuits. Fortunately, there are a variety of ways to handle these common-mode problems. Essentially, filtering relies on blocking noise through absorption or shunting noise via low inductance. In the first technique, components utilize the ferrite family of dielectrics. For the latter, ceramic capacitors might be used. A previous article[2] compared insertion loss test results of the X2Y® ceramic with those obtained using inductors, standard capacitors, and a dual-line ferrite—passive components commonly used for filtering both modes. Test results from that comparison showed a single X2Y component significantly outperformed all the other devices on a consistent basis. For this article, a solution for filtering these two modes using ceramic capacitors will be used to highlight the structural advantages of an emerging new technology over the old designs.

One common practice in filtering both common-mode (CM) and differential-mode (DM) noise is to use three capacitive elements—two "Y" caps for shunting the CM noise from each line to ground and a single "X" cap for shunting DM noise line-to-line as shown in Figure 2.

It would seem reasonable given the definition of CM noise that two closely matched (capacitively) Y caps would be the most effective way to shunt the noise evenly to ground so as to attain maximum attenuation. However, closely matched capacitors require sorting by the manufacturer and carry an added cost that must be absorbed by the customer.

Moreover, all matching efforts can easily be undone if careful, equal placement of the two caps is ignored. In the simple circuit model of a standard capacitor (Figure 3), the resistance, inductance and capacitance are in series.[3] In this design, the external cap mounting, the vias, the traces and the board layers to which they are attached must all be in series with the capacitor as well.

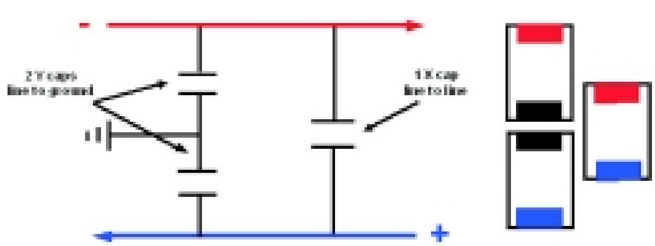


Figure 2. Dual-line filtering using three standard capacitors.

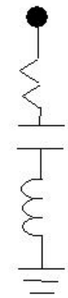
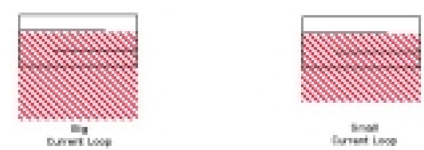


Figure 3. Simple circuit model for a standard capacitor.

Any variation in trace or lead length will change the loop size formed by the mounted capacitor and alter the (L) factor (Figure 4).



$$f_{RS} = \frac{1}{2\pi\sqrt{LC}}$$

Resonant frequency formula

Figure 4. Variation in loop size can cause imbalance in filtering.

Current loop size is a dominant factor in determining inductance, and hence impacts capacitor self-resonance frequency. Similarly, variation in the loop size of the two "matched" capacitors will affect insertion loss for each line and cause an imbalance. This imbalance would be more prominent in higher speed circuits.

When filtering differential-mode noise, an X cap is used to shunt noise from one line to the other through the low impedance of the capacitor, thus returning the noise to the EMI source (Figure 5).

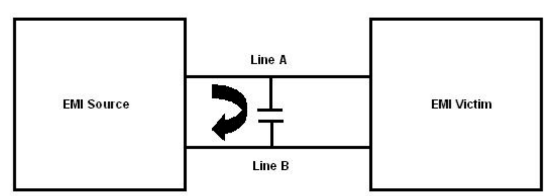


Figure 5. An X cap returns differential-mode noise to source.

Again, since a single standard capacitor has its lowest impedance at its self-resonance frequency[4], multiple X capacitors would be needed to shunt differential-mode noise on a broad frequency spectrum. Finally, three separate components, no matter how evenly matched or carefully placed in a circuit, will attenuate circuit noise to different levels and at different moments in time, thus creating an imbalance that propagates as noise. One way to overcome all of these factors would be to combine all three passive components and their intended function inside one device.

STRUCTURAL IMPROVEMENT

X2Y technology takes the standard two-plate multi-layer technology and inserts three commonly terminated electrodes between each plate (Figure 6).

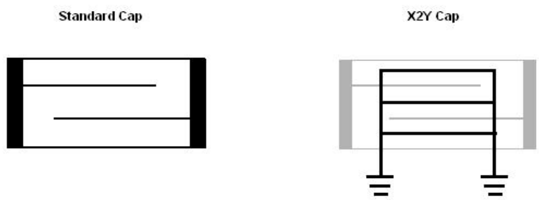


Figure 6. Note: In both components, repeating the "core structure" will increase capacitance by increasing total plate area.

These three new electrode plates are then terminated to the sides of the component forming a four-terminal cap. To create a new component, essentially a dual-line filter, the original two-plate portion of the device is attached between oppositely phased or charged conductors, and additional plates are attached to a ground (Figure 7). As the component is energized and as capacitance develops between the electrode plates through the dielectric, a circuit is formed which consists of an X capacitor and two Y capacitors, hence the name, X2Y. Note that there are three electrode plates in the X2Y, while standard caps require six plates. The two "hot" and one ground electrode in the X2Y thus provide two different functions simultaneously. The main purpose of the remaining two ground electrodes shown in the schematic is shielding, which boosts functional efficiency.

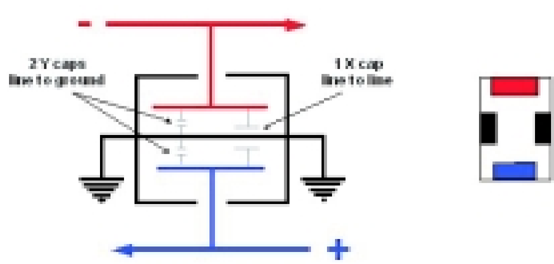


Figure 7. Schematic representation of the X2Y Circuit.

The "hot electrodes" within the component are shielded by the ground electrodes and serve to trap the inductive and capacitive parasitics found in standard capacitor design. Also, because both hot electrodes share the center ground electrode, simultaneous E- and H-field cancellation occurs within the part.

As shown in Figure 8, the E-field is distributed evenly throughout the part with the aid of the dielectric, and charge cancellation occurs on the shared ground electrodes. The H-field of the opposing noise currents from each conductor follow the right hand rule and are 180 degrees out-of-phase. Evenly spaced layers of a multilayer capacitor result in close coupling of the current flux and a high degree of magnetic flux cancellation. The "A" cross-section in Figure 8 shows that each pair of hot electrodes is separated by a ground electrode and the side ground terminations, thus creating current loops that are much smaller than those of standard caps. Because inductance is directly proportional to current loop size, this design yields a very low self-inductance.

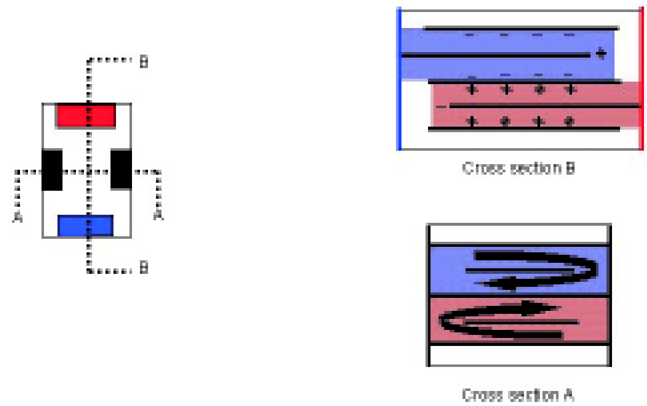


Figure 8. Front and side perspective of X2Y component interior.

Low self-inductance may be a plus, but is of little value when attachment with vias or traces creates a blocking inductance that nullifies the low self-inductance of the part. However, the X2Y's internal design lowers external attachment inductance. When the two side ground terminations of the component are attached to an exterior ground, the internal impedance of the device is in parallel with the ground plane, rather than in series as is the case with standard capacitors (Figure 9).

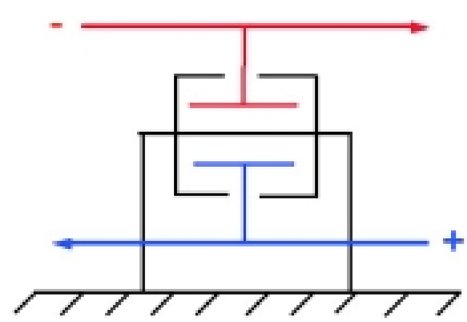


Figure 9. The internal impedance of X2Y is in parallel to the impedance of the ground plane to which is attached.

To illustrate the benefit of a parallel attachment, a test fixture[2] was employed to go through an attachment sequence of the two ground terminations to show change in insertion loss (Figure 10). The shift from a series to a parallel connection is in the data, shown in sequence in

Figures 11 through 13.

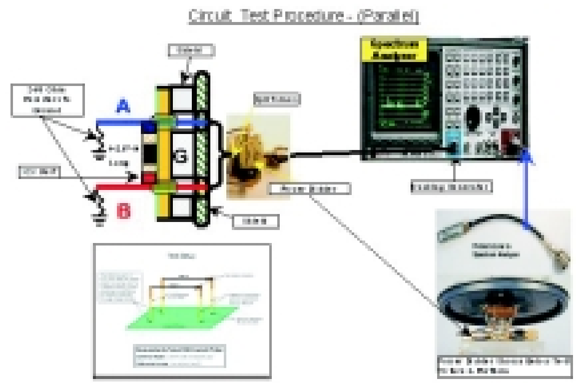


Figure 10. Test setup for parallel sequence measurements.

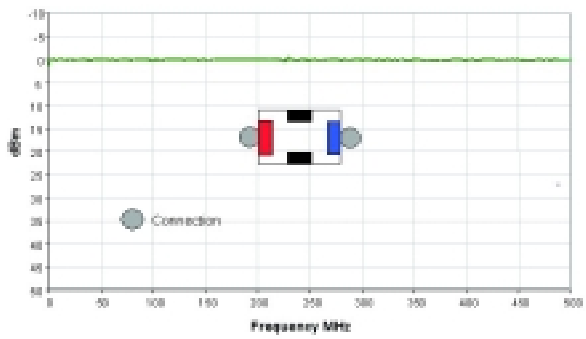


Figure 11. Noise is injected on both lines simultaneously through a splitter. Common-mode test result shows no insertion loss when the component is attached between two leads and is ungrounded.

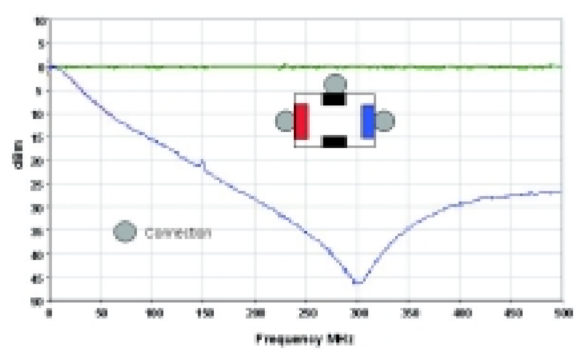


Figure 12. Here, one of the ground terminations (G1) is attached to ground and a circuit resonance at 300 MHz is shown. However, although the internal ground electrodes of the component are in parallel, the external circuit connection is still in series like that of a standard capacitor.

This same fixture was then used to compare the insertion loss performance of three discrete caps to that of a single X2Y ceramic cap. The three discrete caps were mounted with minimal lead length (1/16").

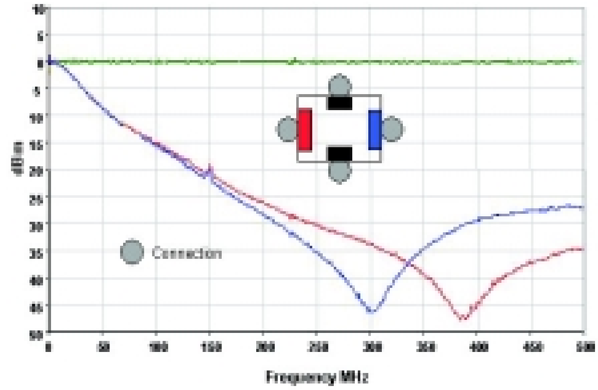


Figure 13. Here, both G1 and G2 are attached. All the internal parallel electrode plates of X2Y are in parallel to the circuit. The resonant frequency of the circuit shifts from 300 MHz to 380 MHz.

Figure 14. Comparison capacitance values of the X2Y cap and three discrete caps.

The capacitance value of the three discrete caps when measured in the circuit was 0.66 µF for each of the 2 Y caps and 0.40 µF for the X cap (Figure 14). The X2Y follows a dual stacked TEM Cell model when measured for capacitance[5]. The two Y caps each measure C and the X cap measures 1/2 C. The X2Y measured 0.66 uF on each of the two internal Y caps and the X cap value was 0.33 µF, slightly lower than the discrete X value but not considered significantly so. Noise was injected simultaneously on both lines (CM) through a splitter and was measured for common-mode insertion loss.

Test results show that the three discrete caps tracked the X2Y by 10 dB throughout the frequency ranges shown (Figures 15 and 16). Also, a comparison test was run on the X2Y in the two-hole discoidal format. Results of that test show a significant improvement with less capacitance (0.22 µF two Ys, 0.11 single X). This outcome would be expected with the improved grounding provided by the 360-degree soldering of the ground termination to

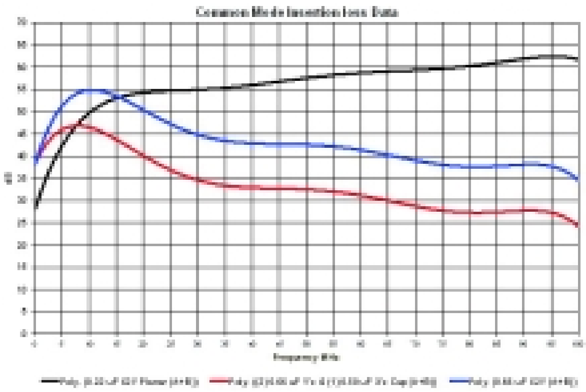


Figure 15. Ceramic cap comparisons to 100 Mhz.

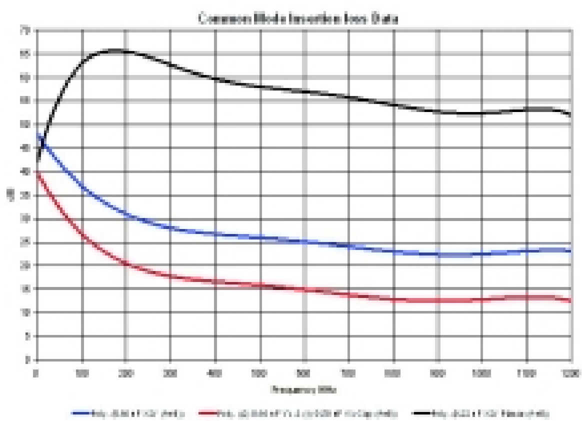


Figure 16. Ceramic cap comparisons to 1200 MHz.

the fixture, and which allows for increased current spreading on the ground electrodes, and increased noise cancellation within the X2Y. [Note: All data from this test fixture are shown using a 6-point poly average.]

The X2Y structure manufactured in ceramic dielectric yield the following benefits:

1. Same standard component package sizes/cap values currently used in industry.
2. Two balanced Y capacitors, 1 to 3% when measured line-to-ground.
3. Equal aging and temperature tracking on each Y cap to maintain balanced performance.
4. Equalized voltage versus capacitance variation line-to-line, especially beneficial when using dielectrics such as Y5V.
5. Reliability increases when using a single X2Y component vs. three standard caps.

Many of the benefits highlighted so far can be attributed to the X2Y'sunique internal design and its connection in a circuit and were patented as "dielectric independent."

X2Y in ceramic is ideally suited for filtering dual-mode noise in 12 V DC motors (documented in an earlier article[6]) used in automotive applications. Data from that article showed that a single X2Y replaced as many as seven passive filter elements combined for filtering broadband emissions.

However, filtering high-speed data lines that use differential signaling can be more difficult when using capacitors. Line-to-ground capacitance can have a negative effect on signal integrity because of signal distortion. Therefore, low capacitance values must be used, effectively creating a low-pass filter. Ferrites are commonly used as a solution in these applications because the inductive nature of ferrite dielectric material allows for low signal distortion. The X2Y structure has been manufactured in ferrite material to investigate the possibility of gaining broadband filtering for these "signal sensitive" circuits.

FERRITE COMPARISON TESTING (CM)

For this testing, common-mode insertion loss was measured on three devices used for dual-line filtering (Figure 17). Two X2Y ferrite samples in EIA size 0805 and 1206 were provided by Steward, a leading manufacturer of ferrite based products. A dual-line common-mode choke was compared as well.

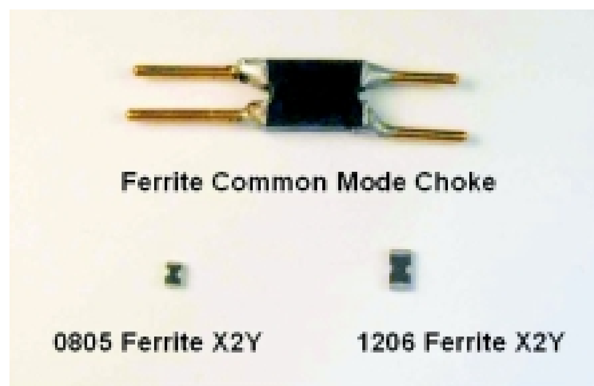


Figure 17. Dual-line ferrite structures.

The graphs in Figures 18 and 19 show that the X2Y ferrite devices provided a significant improvement in insertion loss above 100 MHz for the 1206 and above 250 MHZ for the 0805, when compared to the much larger dual-line structure. The X2Y is in bypass within the circuit and requires only enough ferrite material to filter noise currents (RF). The dual-line ferrite is in feedthrough with the DC current and therefore requires larger mass to accommodate the DC current of the lines. Other data generated, where two 1206s were stacked to provide greater mass (not shown), indicated that larger 1812 samples that are near completion will provide higher insertion loss in the lower frequencies than the dual-line common-mode choke.

FERRITE TESTING CM & DM

Amphenol Aerospace (AAO), a manufacturer of EMI filter connectors for the military, aerospace and industrial

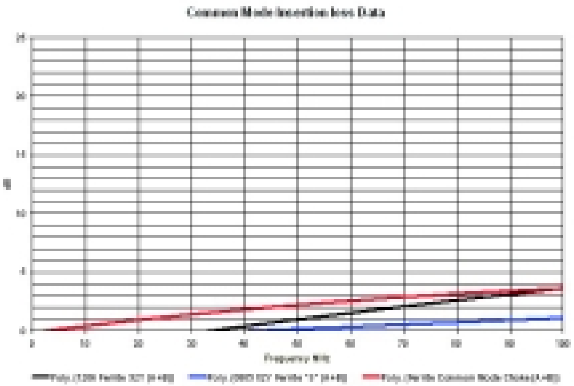


Figure 18. Ferrite structure comparisons to 100 MHz.

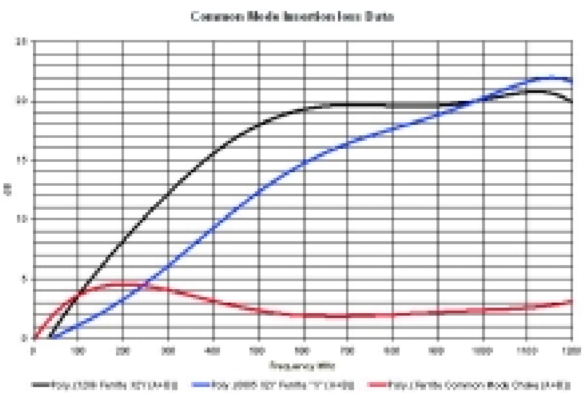


Figure 19. Ferrite structure comparisons to 1200 MHz.

markets since 1966, has been following the X2Y technology for some time. In the interest of product verification and applicability to their customers, they agreed to perform additional testing on the ferrite capacitors. Many of their products are complex signal devices that require high-frequency filtering and protection, (*i.e.*, squib devices, high-speed data networks, etc.). These applications require differential-mode protection because the noise source is often internal and the ground reference is not the housing or chassis but an internal circuit that has a noise reference between the signal or power lines. The X2Y capacitor, in either a chip format or planar format, offered AAO significant advantages in performance and assembly and therefore merited test evaluation. Using ferrite material as the basis for a capacitor is a unique approach to meet the needs of higher frequency applications. Ferrite material is ideally suited to provide low capacitance, satisfactory insertion loss, and minimal signal distortion.

Since test measurements in the X2Y comparison fixture at that point had been on common-mode noise, AAO designed an insertion loss fixture for measuring both noise modes. The ferrite material used in the X2Y 1206 samples provided by Steward had a line-to-ground capacitance of 435 pF and line-to-line capacitance of 212 pF when measured on a standard capacitance bridge at 1 kHz. Using an impedance bridge, the capacitance decreased with frequency. When measured, it rolled off to 60 pF at 1 MHz. Insertion loss was measured using a network analyzer sweeping between 100 kHz to 200 MHz.

Figure 20. Mounting shield used in test setup.

Each chip capacitor was mounted onto a circular PCB with the A and B electrodes connected to pins that passed through the PCB, the two grounds (G1 & G2) connected to the common ground. The PCB with a circular spring in contact with the board ground plane was installed into a simulated connector housing. The connector housing was then attached to a bulkhead (Figure 20) that was mounted to a metal, silver-plated can that prevented signals from leaking around the bulkhead. The signal source was grounded to the bulkhead. The signal was then fed into a pin and the resultant signal level was measured on the opposite side of the bulkhead on the same contact. This produced a common-mode insertion loss similar to the rating for existing filter connectors. Additionally, insertion loss was measured with the signal fed into one contact and with the resultant signal measured on the opposite side of the bulkhead at the output of the adjacent pin. This gave the differential-mode insertion loss.

Test results in Figure 21 show that the through-pin common-mode insertion loss was 19 dB to 22 dB at 200 MHz. The insertion loss measured between pins, differential mode, measured 51 db to 55 dB at 200 MHz. The common-mode insertion loss started at about 4 dB at 100 kHz. The differential mode started at about 90 dB at 100 kHz decreasing to about 45 dB at 30 to 40 MHz. Insertion loss rolled up to stabilize at 110 MHz and remained flat out to 200 MHz. The common-mode slope appears to be 10 dB per decade and stable.

The insulation properties of the X2Y device were measured as well. The insulation resistance of the ferrite capacitor at 50 volts was on the order of 30 GW. It was checked to 200 volts without breakdown. Further testing will be needed to see how the devices behave out to

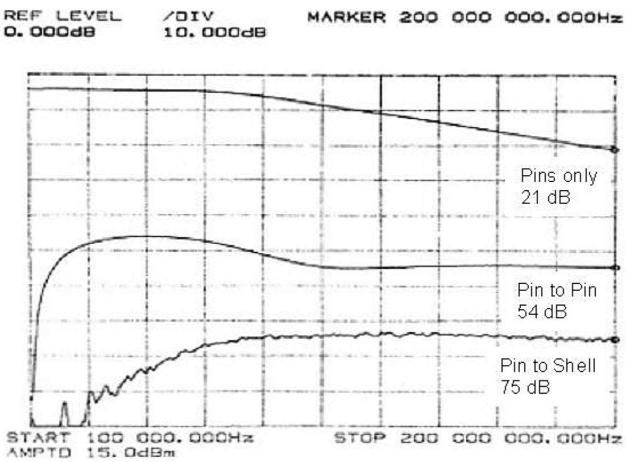


Figure 21. X2Y ferrite insertion loss measurements.

several GHz and to determine the effect of pass-through current on the insertion loss.

The X2Y ferrite devices were shown to have significant insertion loss performance while offering very little capacitance, making them ideal for high frequency applications. Other possible benefits were noted. By mounting the device on a ground plane that can be made common to a connector shell, a Faraday cage is formed. This design would contain even more internal noise and would prevent external noise from entering the system.

FINAL CONCLUSIONS

The test results showing insertion loss for the X2Y ferrite components point towards a promising solution for separation of noise from signal in high-speed circuits. Preliminary insertion loss measurements in a microwave test fixture by Steward, the sample manufacturer, showed differential insertion loss of 80 dB at 1 MHz and 27 dB out to 6 GHz. The benefits of the X2Y structure continue to be investigated in other dielectrics as well. X2Y samples in metal oxide varistor (MOV) dielectric show excellent high frequency filter characteristics. Samples in film dielectric are feasible.

The structure itself warrants investigation with today's modeling software. However, the simultaneous function of the X and Y capacitors within the component and the minimal size of the device will present unique challenges. Modeling of the structure would be useful to see if the functional benefits of this technology can be transposed into other electronic components, passive or active, to improve circuit performance and EMC compliance.

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A complete portfolio listing of X2Y® Technology can be accessed at www.x2y.com.