All Ferrite Beads Are Not Created Equal - Understanding the Importance of Ferrite Bead Material Behavior

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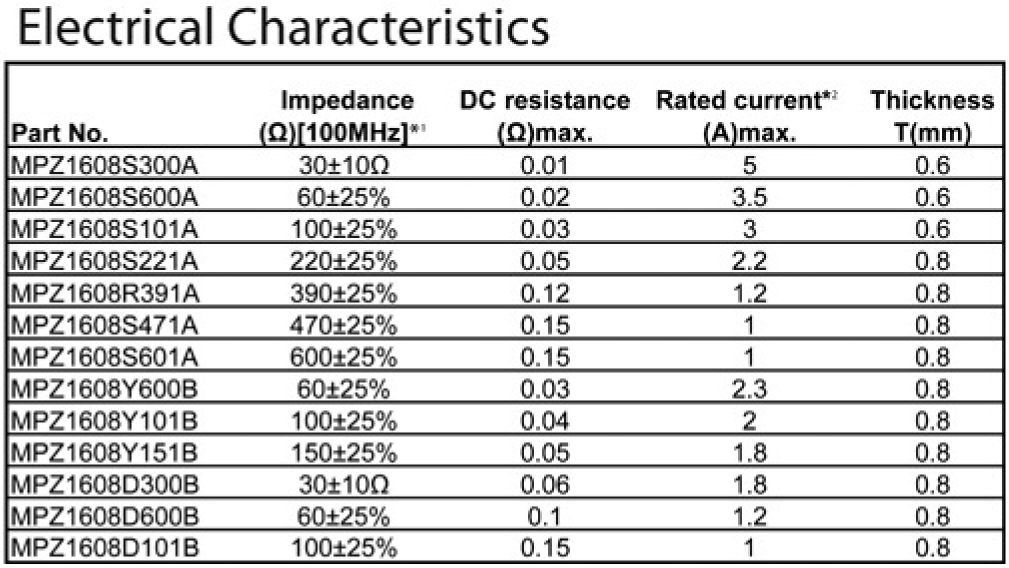
A common scenario: A design engineer inserts a ferrite bead into a circuit experiencing EMC problems, only to find that the bead has actually caused the unwanted to noise to be WORSE. How can this be? Aren't ferrite beads supposed to remove noise energy and not make the problem worse?

The answer to this question is fairly simple, but may not be widely understood outside of those who work a majority of their time solving EMI issues. Simply put, a ferrite bead is not a ferrite bead is not a ferrite bead, etc. Most ferrite bead manufacturers provide a table which lists their part number, the impedance at some given frequency (usually 100 MHz), the DC resistance (DCR), a maximum current rating and some dimensional information (see Table 1). All pretty much standard stuff. What is not shown in the data table is material information and the respective performance characteristics over frequency.



Electrical Characteristics

Part No.	Impedance (Ω)[100MHz]*1	DC resistance (Ω)max.	Rated current*2 (A)max.	Thickness T(mm)
MPZ1608S300A	30±10Ω	0.01	5	0.6
MPZ1608S600A	60±25%	0.02	3.5	0.6
MPZ1608S101A	100±25%	0.03	3	0.6
MPZ1608S221A	220±25%	0.05	2.2	0.8
MPZ1608R391A	390±25%	0.12	1.2	0.8
MPZ1608S471A	470±25%	0.15	1	0.8
MPZ1608S601A	600±25%	0.15	1	0.8
MPZ1608Y600B	60±25%	0.03	2.3	0.8
MPZ1608Y101B	100±25%	0.04	2	0.8
MPZ1608Y151B	150±25%	0.05	1.8	0.8
MPZ1608D300B	30±10Ω	0.06	1.8	0.8
MPZ1608D600B	60±25%	0.1	1.2	0.8
MPZ1608D101B	100±25%	0.15	1	0.8

Table 1: Typical Ferrite Bead Data Table

What Is a Ferrite Bead?

A ferrite bead is a passive device that removes noise energy from a circuit in the form of heat. The bead creates impedance over a broad frequency range that eliminates all or part of the undesired noise energy over that frequency range. For DC voltage applications (such as Vcc lines for ICs), it is desirable to have a low DC resistance value as to not have large power losses within the desired signal and/or voltage or current source (I2 x DCR losses). However, it is desirable to have high impedance over some defined frequency range. Therefore, the impedance is related to the material used (permeability), the size of the ferrite bead, the number of windings and the winding construction. Obviously, the more windings within a given case size and for a specific material used, the higher the impedance, but this will also yield higher DC resistance as the physical length of the inner coil is longer. The part's rated current is inversely proportional to its DC resistance.

One of the fundamental aspects of using ferrite beads for EMI applications is that the component must be in its resistive stage. What does this mean? Simply, it means that "R" (AC resistance) must be greater than "X_L" (inductive reactance). At frequencies where $X_L > R$ (lower frequencies), the part behaves more as an inductor than a resistor. At frequencies where $R > X_L$, the part behaves as a resistor which is the desired property of the ferrite bead. The frequency, at which "R" becomes greater than "X_L," is called the "cross-over" frequency. This is shown in Figure 1 with the cross-over frequency marked, 30 MHz in this example, by the red arrow.

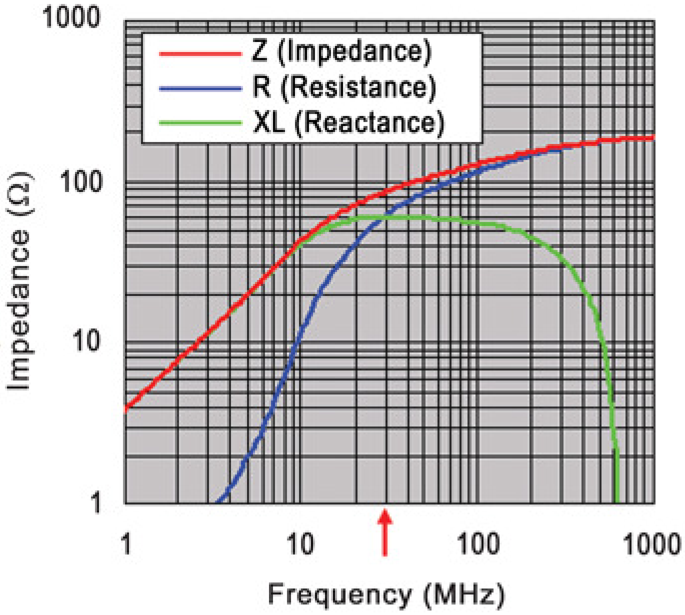


Figure 1: Cross Over Frequency

Another way to look at this is in terms of what the part is actually doing while in its inductive and resistive stages. Like other applications where there is an impedance mismatch with inductors, part of the introduced signal is reflected back to the source. This can provide some protection for sensitive devices on the other side of the ferrite bead, but also introduces an “L” into the circuitry and this can cause resonances and oscillations (ringing). So when the bead is still inductive in nature, part of the noise energy will be reflected and some percentage will pass through, depending on the inductance and impedance values.

When the ferrite bead is in its resistive stage, the component behaves, as stated, like a resistor and therefore impedes the noise energy and absorbs this energy from the circuit and does so in the form of heat. Though constructed in an identical manner as some inductors, using the same processes, manufacturing lines and techniques, machinery and some of the same component materials, the ferrite bead uses a lossy ferrite material while an inductor utilizes a lower loss ferrite material. This is shown in curves of Figure 2.

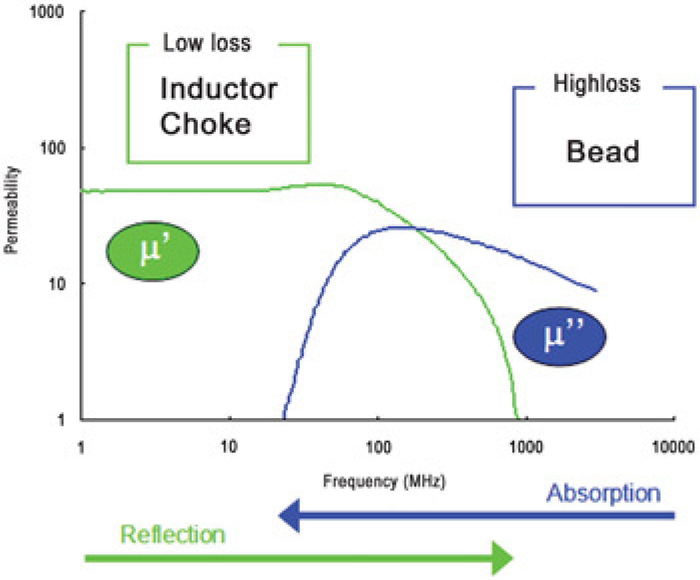


Figure 2: Reflection vs. Absorption

This figure shows [μ''] which is used to reflect the behavior of the lossy ferrite bead material.

Differences in Ferrite Materials

The fact that impedances are given at 100 MHz is also part of the selection problem. In many EMI cases, the impedance at this frequency is irrelevant and misleading. This "spot" value does not state if the impedance is increasing at this frequency, decreasing, flat, peaked in impedance, whether the material is still in its inductive stage or has transformed into its resistive stage. In fact, many ferrite bead suppliers use multiple materials for the same perceived ferrite beads, or at least as shown in the data table. See Figure 3. All five curves in this figure are for different 120 Ohm ferrite beads.

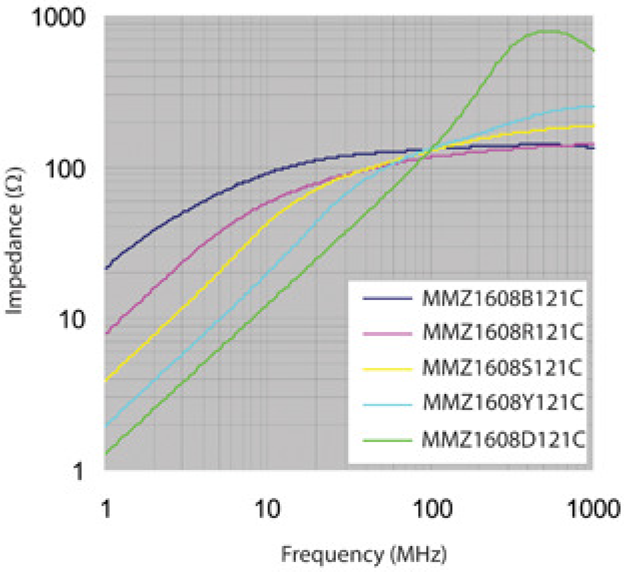


Figure 3: 120 Ohm (at 100 MHz) Ferrite Beads

What the user must obtain, then, is the impedance curve that shows the frequency characteristics of the ferrite bead. An example of a typical impedance curve is shown in Figure 4.

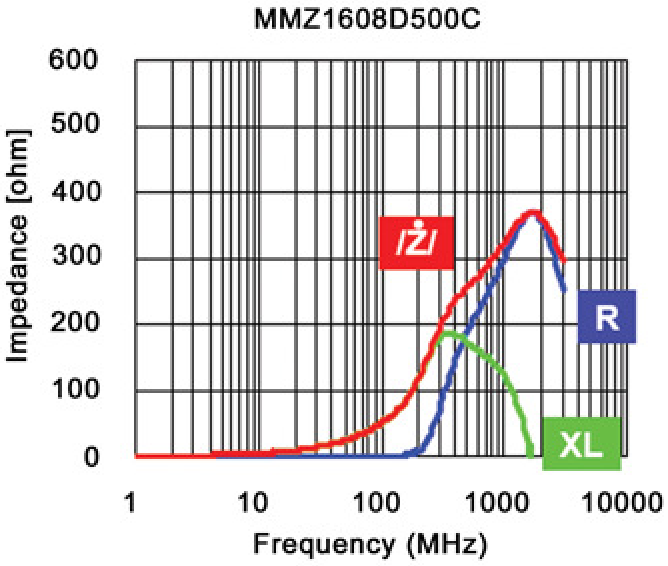


Figure 4: Typical Impedance Curve with /Z/, R, XL

Figure 4 shows a very important fact. The part is specified as a 50 Ohm ferrite bead, at 100 MHz, but its cross-over frequency is roughly 500 MHz, and it achieves over 300 Ohms between 1 and 2.5 GHz. Again, by simply looking at the data table would not allow the user to know this and can be very misleading.

As shown, materials vary in their performance. There are numerous variations of ferrite used in the construction of ferrite beads. Some materials are high loss, wide frequency, high frequency, low insertion loss and others. A general grouping by application frequency and impedance is shown in Figure 5.

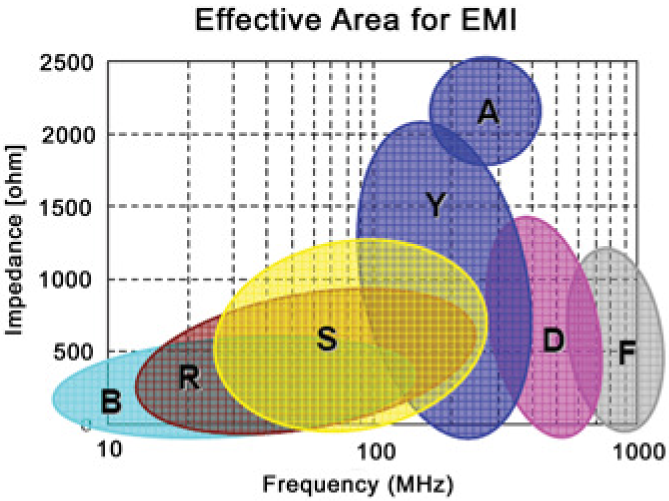


Figure 5: Material Characteristics Based Upon Frequency[1]

Another common problem is that the board designer is sometimes limited in ferrite bead choices by what is in their approved component database. If the company has only a few approved ferrite beads which have been used on other products and were deemed satisfactory, in many cases there is no perceived need to evaluate and approve other materials and part numbers. This has many times, in the recent past, led to some of the worsening effects of the original EMI noise problem mentioned above. What worked before may or may not work on the next project. One can't simply carry over the last project's EMI solution, especially if the frequency has changed for the desired signal or there are frequency changes in potentially radiating components such as clock devices.

Comparing Cross-Over Frequencies

If one takes a look at the two impedance curves in Figure 6, a comparison can be made of the material effects of two similar specified parts.

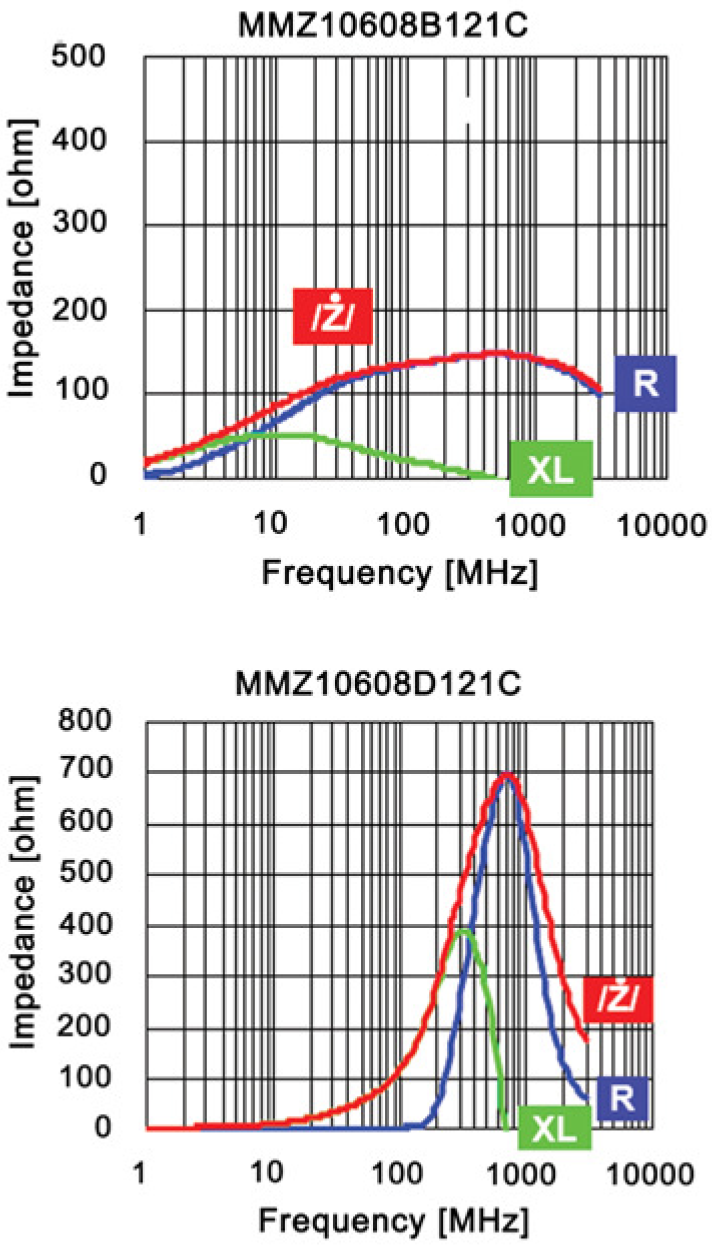


Figure 6: Impedance Curves for B Material (top) and D Material (bottom)

For both parts, the impedance at 100 MHz is 120 Ohms. For the part on the left, using the “B” material, the maximum impedance is around 150 ohms and is achieved at 400 MHz. For the part on the right, using the “D” material, the maximum impedance is 700 Ohms as is achieved at approximately 700 MHz. But the biggest difference is in the cross-over frequencies. The super high loss “B” material transitions (R > XL) at 6 MHz while the very high frequency “D” material remains inductive until around 400 MHz. Which is the right part to use? It depends on each individual application.

Actual Example

Figure 7 demonstrates an all too common problem that arises when the wrong ferrite bead is chosen to suppress EMI. The unfiltered signal demonstrates a 474.5 mV undershoot on a 3.5V, 1 uS pulse.

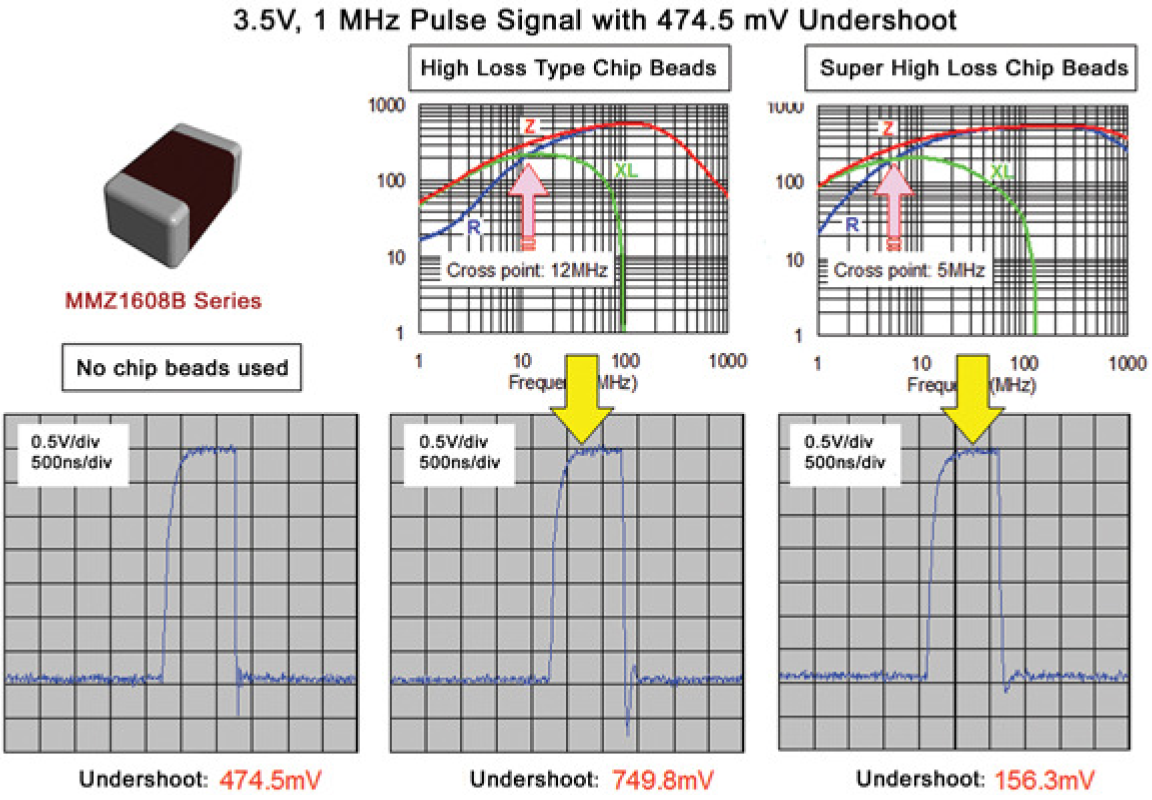


Figure 7: Measured Performance of High Loss and Super High Loss Materials

In the result using the High Loss type material (center plot), the measured undershoot is increased due to the part's higher cross-over frequency. The signal undershoot is increased from 474.5 mV up to 749.8 mV. The Super High Loss material, with its lower cross-over frequency, performs adequately and would be the right material to use in this application (plot on right). The undershoot using this part is reduced to 156.3 mV.

DC Bias Phenomenon

As the DC current through the bead increases, the core material begins to saturate. For inductors, this is called the saturation current and is specified as some percentage decrease in the inductance value. With ferrite beads, while the part is in its resistive stage, the effect of saturation is reflected in the reduction of impedance values over frequency. This drop of the impedance reduces the effectiveness of the ferrite bead and its ability to remove EMI (AC) noise. Figure 8 shows a set of typical DC bias curves for a ferrite bead.

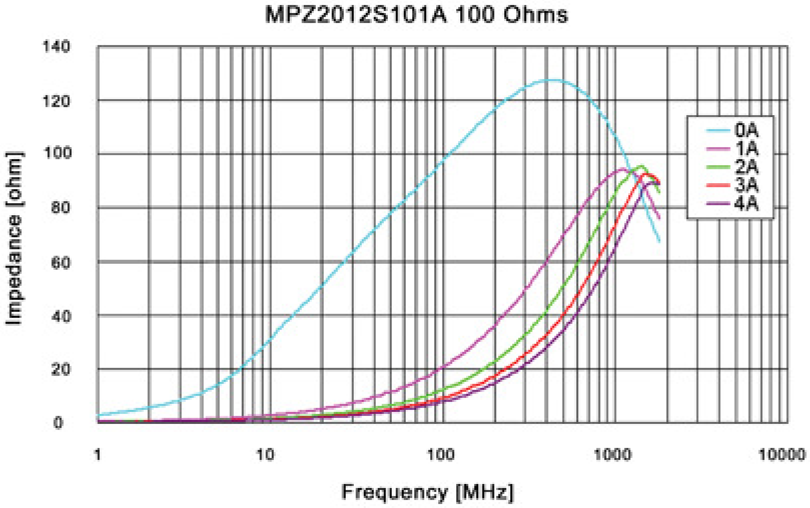


Figure 8: Effects on Impedance by DC Current

In this figure, the ferrite bead is rated at 100 Ohms at 100 MHz. This is the typical measured impedance when there is no DC current through the part. But as can be seen, once a DC current is applied (such as for IC VCC inputs), there is a sharp drop-off of effective impedance, going from 100 Ohms to 20 Ohms in the above curves for just a 1.0 A current at 100 MHz. Maybe not too critical, but something the design engineer must be aware of. Again, by using only the parts' electrical characteristic data from the supplier's datasheet, the user would have no knowledge of this DC bias phenomenon.

Frequency Response vs. Winding Construction

As with high frequency RF inductors, the winding direction of the inner coils within the ferrite bead has a large impact on the frequency behavior of the bead. The winding direction influences not only the impedance versus frequency levels, but also shifts the frequency response. In Figure 9, two 1000 Ohm ferrite beads, in the same case size and made of the same material but with two different winding configurations, are shown.

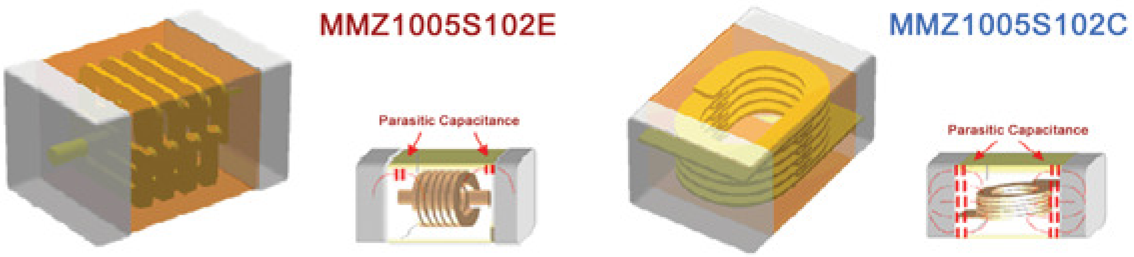


Figure 9: "Giga" Bead on Left, Standard Bead on Right[2]

The part on the left, with coils wound in the vertical plane and stacked in the horizontal direction, yields higher impedance and a higher frequency response than the part on the right which is wound in the horizontal plane and stacked in the vertical direction. This is, in part, due to the lower capacitive reactance (XC) associated with the reduced parasitic capacitance between the end terminations and the inner coils. The lower XC creates a higher self resonance frequency which then allows the ferrite bead to continue to increase in impedance up to the higher self resonance frequency, resulting also in a higher obtainable impedance value than possible with a standard constructed ferrite bead. The curves for the above two 1000 Ohm ferrite beads are shown in Figure 10.

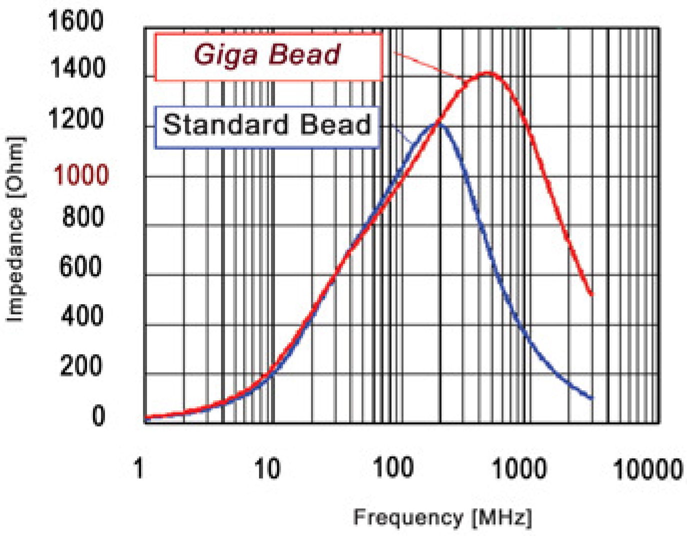


Figure 10: Comparison of Frequency Response Due to Winding Configuration

Actual Test Results

To further show the impact of correct and incorrect ferrite bead selection, a simple test circuit and test board were used to demonstrate much of what has been discussed above. In Figure 11, a test board is shown with three ferrite bead locations and test points labeled as “A”, “B”, and “C” at 0 mm, 50 mm, and 100 mm distance from the output of the transmitting (TX) device, respectively.

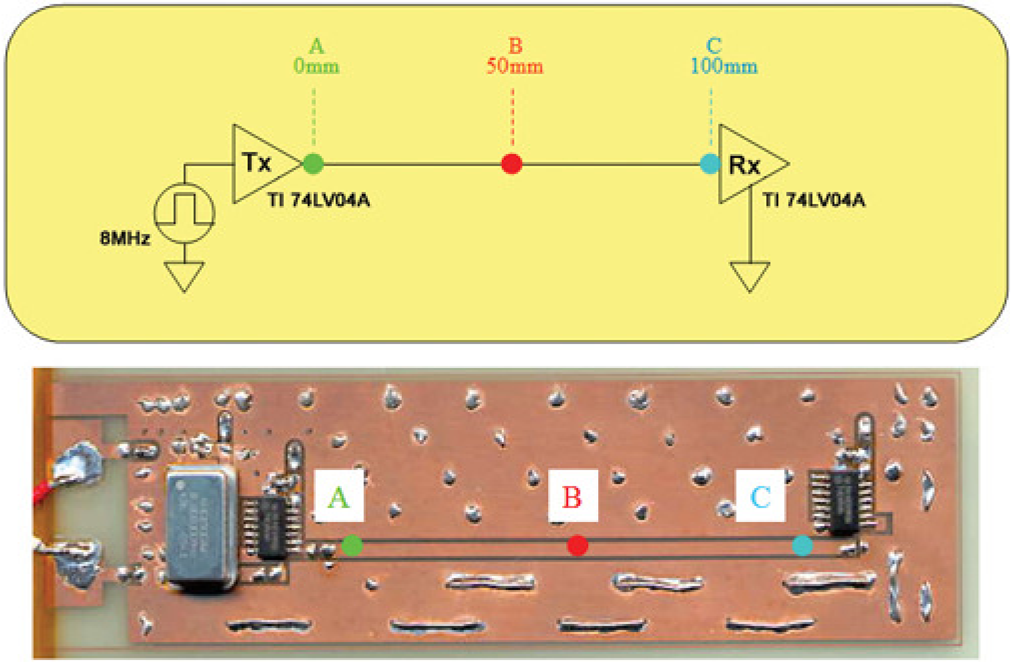


Figure 11: Test Setup and Test Board

Signal conditions for this test were the following:

Frequency:	8 MHz
Duty Cycle:	50%

High voltage:	5V
Low voltage:	0V
Rise time:	1.6 nS
Fall time:	1.8 n

The signal integrity was measured on the output side of the ferrite bead at each of the three locations and duplicated with two ferrite beads made of different materials. The first material, a low frequency, lossy “S” material was tested at points “A,” “B” and “C”. Next, a higher frequency “D” material was used. The point to point results using these two ferrite beads are shown in Figure 12.

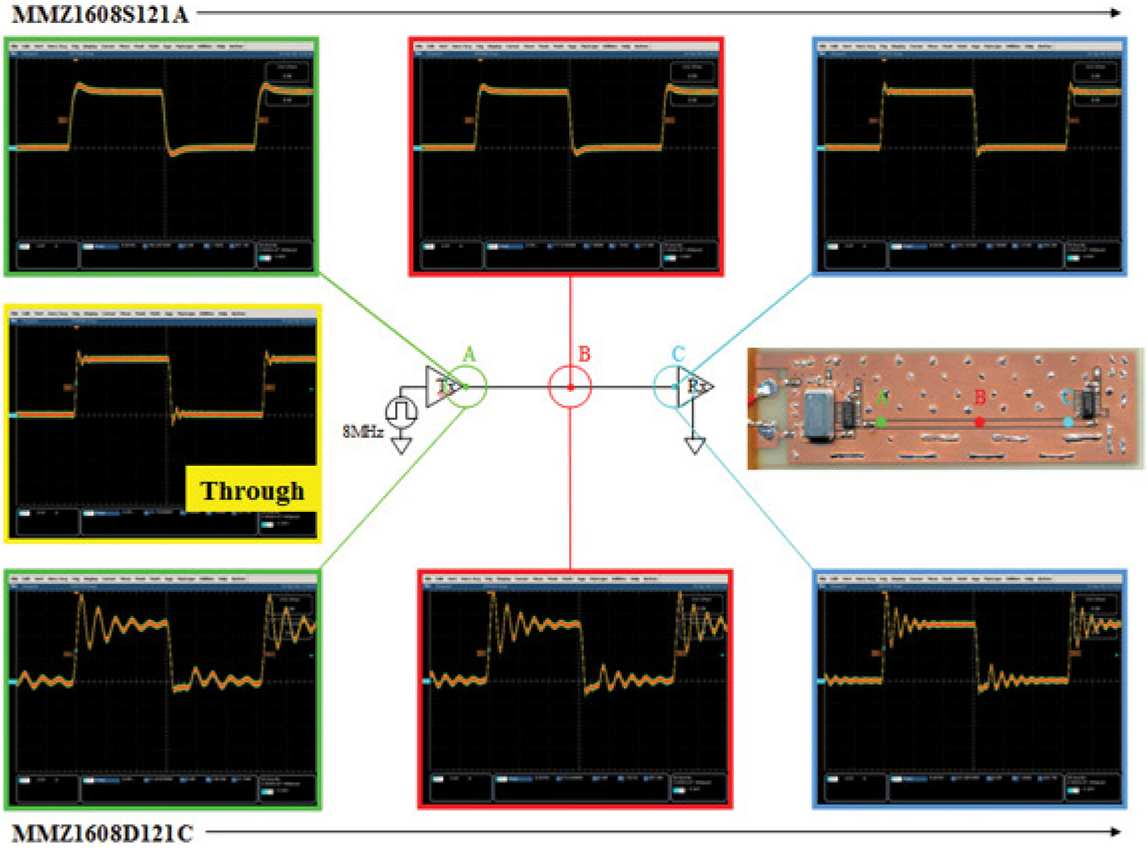


Figure 12: In-Circuit Performance Testing Results

The “through” unfiltered signal is shown in the center row and exhibits some overshoot and undershoot on the rising and falling edges respectively. As can be seen, with the use of the correct material for the above test conditions, the lower frequency, lossy material exhibited good overshoot and undershoot signal improvement on the rising and falling edges. These results are shown in Figure 12 in the upper row. The results using the high frequency material caused ringing that magnified the levels of each and increased the period of instability. These test results are shown in the bottom row.

When looking at the improvement on EMI over frequency for the recommended upper part (in Figure 12) in the horizontal scan shown in Figure 13, it can be seen that this part substantially reduces the EMI spikes and reduces the overall noise levels, for all frequencies in the 30 to approximately 350 MHz range, to an acceptable level well below the EMI limit highlighted by the red line, which is the general regulatory standard for Class B devices (FCC part 15 in the US). The “S” material used in the ferrite bead is specifically for these lower frequencies. And as can be seen, the “S” material has limited impact on the original, unfiltered EMI noise levels once the frequency gets above 350 MHz, but does reduce the one major spike at 750 MHz around 6 dB. If the major portion of the EMI noise problem was above 350 MHz, one would need to look at using a higher frequency ferrite material that has its impedance maximum higher in the frequency spectrum.

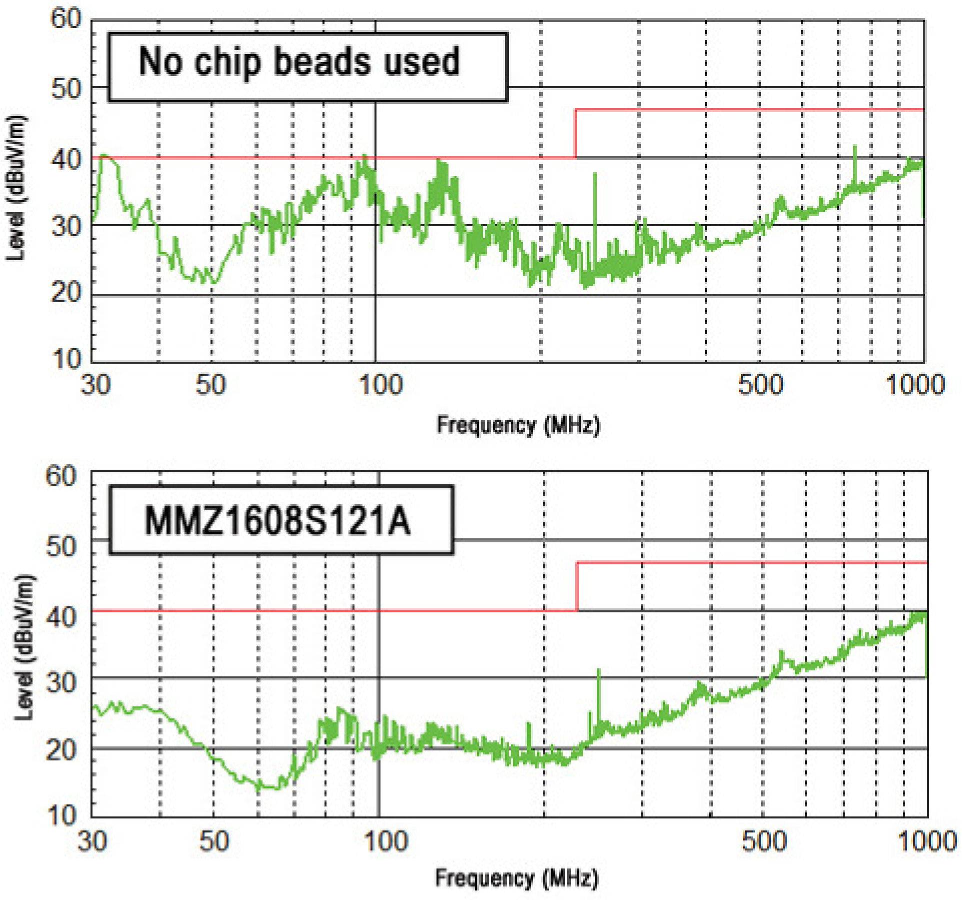


Figure 13: Radiated EMI Noise (Horizontal) Suppression

Of course all of the ringing, shown in the bottom curves in Figure 12, is typically avoided by actual performance testing and/or simulation software, but it is hoped that this article will allow the reader to bypass a lot of the common errors, decrease the amount of time needed to select the correct ferrite bead and allow for a more "educated" starting point when a ferrite bead is needed to help solve an EMI issue.

Conclusion

To avoid misuse in your future ferrite bead needs, it is recommended that you always:

1. Understand the noise problem within your circuit, including noise sources
2. Choose the correct material behavior needed, e.g., high loss at low frequencies
3. Determine the allowable trade-off for DC resistance and needed AC impedance
4. Get the impedance curve and other data for the part to be used
5. Don't automatically use what has worked before
6. Don't assume that a ferrite bead will be the best EMI component to use
7. If in doubt, contact your ferrite bead supplier as they will have EMI experts

In closing, it is desirable to approve families or series of ferrite beads, not just individual part numbers, to have more options and design flexibility. It needs to be noted that different suppliers use different materials, and it is a must that the frequency performance of each be reviewed, especially when doing multiple sourcing for the same project. This is somewhat easy to do on a first time basis, but once parts are entered into a component database under one control number, and they can be used anywhere thereafter, it is important that the frequency performance of the different suppliers' parts closely resemble each other in order to eliminate potential future problems for other applications. The best way to do this is to have similar data from the various suppliers and, as a minimum, have the impedance curve. This will also ensure the right ferrite bead is being used to solve your EMI problem.

And remember, not all ferrite beads are created equal.

Notes

1. Material designations "B," "R," "S," "Y," "A," "D" and "F" are those of the author's company only and reflect different frequency behavior. Other ferrite bead suppliers have their own material designations.
2. "Giga" is a product name of the author's company only.

Chris Burket has been with TDK since 1995 and is now a senior applications engineer supporting a vast array of passive components. He has been involved in product design, technical sales and marketing. Mr Burket has written and presented technical papers at numerous forums. Mr. Burket had been awarded three U.S. patents in optical/mechanical switches and in capacitors. Mr. Burket can be reached at cburket @incompliancemag.com.

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