Using cable ferrites for interference suppression

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1. Introduction

One of the most used yet least understood techniques for reducing both incoming and outgoing RF interference is the application of ferrite sleeves to cables and at interfaces. This tutorial is meant to shed some light on the use of ferrites, and also presents some comparative frequency domain measurements both to illustrate some of the points, and to give designers an idea of what they might expect in using and specifying a ferrite component. These were made by Elmac Services with actual ferrite samples in a specially-designed test jig, using a spectrum analyser and tracking generator. If your company is interested in independent characterization of the ferrites you are using, please get in touch.

2. The effect of magnetic material on a conductor

Current flowing through a conductor creates a magnetic field around it. Transfer of energy between the current and the magnetic field is effected through the "inductance" of the conductor – for a long straight wire the self-inductance is typically 10nH per centimetre length. Placing a magnetically permeable material around the conductor increases the flux density for a given field strength and by doing so increases the impedance of the length that is enclosed.

Ferrite is such a material; its permeability is controlled by the exact composition of the different oxides that make it up (ferric, with typically nickel and zinc) and is heavily dependent on frequency. Also the permeability is complex and has both real and imaginary parts, which translate into both inductive and resistive components (Figure 1) of the impedance "inserted" into the line passed through the ferrite. The ratio of these components varies with frequency – at the higher frequencies the resistive part dominates (the ferrite can be viewed as a frequency dependent resistor) and the assembly becomes lossy, so that RF energy is dissipated in the bulk of the material and resonances with stray capacitances are avoided or damped.

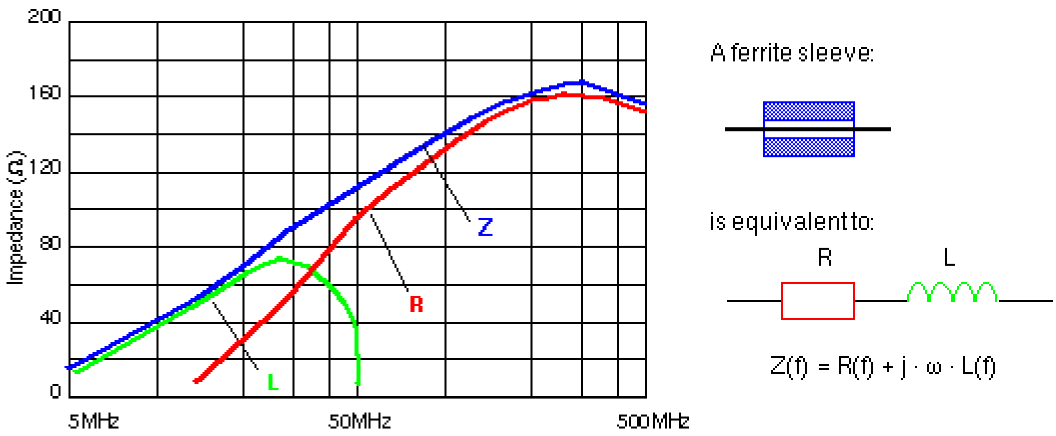


Figure 1 Inductive and resistive components of impedance

3. Common and differential mode cable currents

Differential mode

Cables will normally carry signal and return, and/or power and return, conductor pairs. Multiway cables may carry several such pairs. The magnetic field produced by the intended "forward" current in each circuit pair is almost cancelled by the field produced by its equal and opposite "return" current, provided that the two conductors are close together. Therefore any magnetic material, such as a ferrite sleeve, placed around the whole cable will be invisible to these "differential mode" currents. This will be true however many pairs there are, as long as the total sum of differential-mode currents in the cable harness is zero.

Placing a ferrite around a cable, then, has *negligible effect* on the differential mode signals carried within it, as long as the currents are indeed differential, that is the forward current is equal and opposite to the return current in each circuit.

Common mode

A cable will also carry currents in common mode, that is, all conductors have current flowing in the same direction. Normally, this is an unintended by-product of the cable connection, and the current amplitudes are small (often no more than a few microamps). The source of such currents for emissions is usually either

- ground-referred noise at the point of connection (V_N in Figure 2), which may have nothing to do with the signal(s) carried on the cables, or
- imbalance of the impedance to external ground structures of the various signal and return circuits, so that part of the wanted signal current returns through paths other than the cable harness.

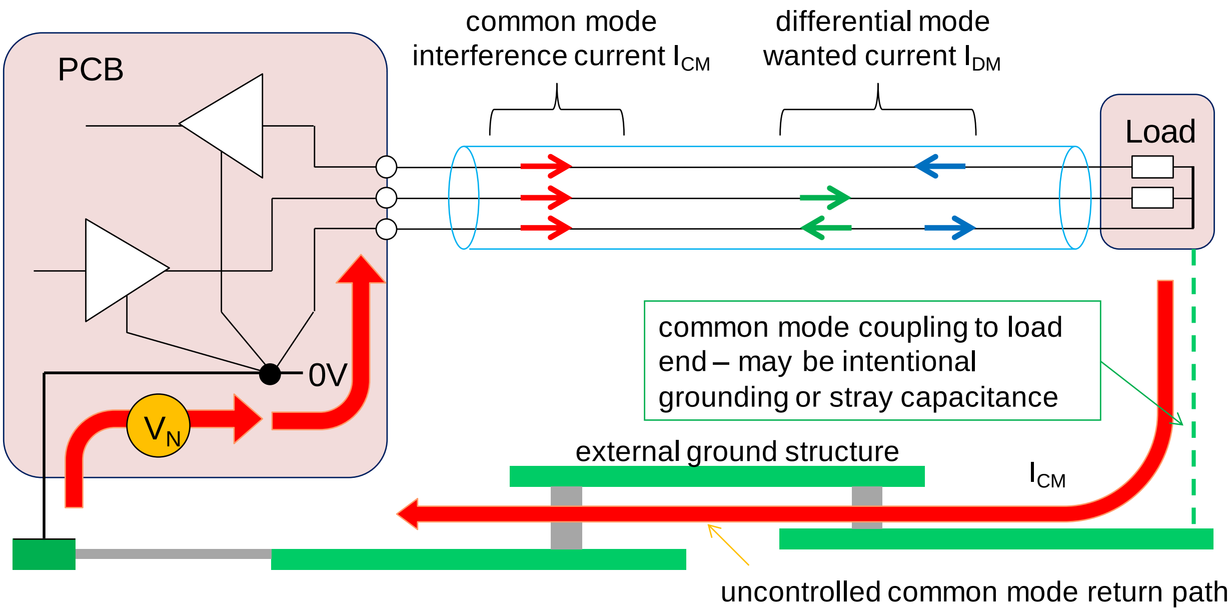


Figure 2 Differential and common mode currents

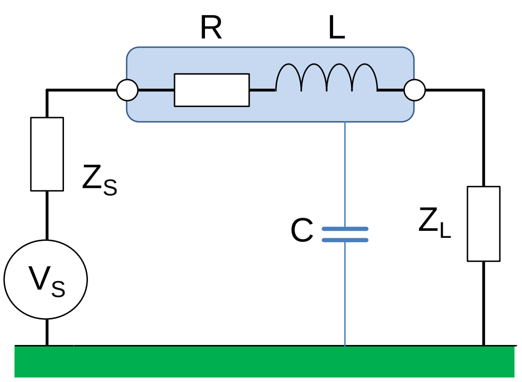
A screened cable may also carry common-mode currents if the screen is not properly terminated to a noise-free reference. Even though the currents may be small, they have a much greater interfering potential since their return path is essentially uncontrolled, there is no cancellation effect, and the cable is acting as if it were a single wire radiating antenna. Also, incoming RF or transient interference currents are generated in common mode and convert to differential mode (and so affect circuit operation) due to differing impedances at the cable interfaces, or within the circuit.

Since common mode currents on a cable *do* generate a net magnetic field around the cable, a ferrite sleeve placed around the cable will *increase* the cable's local impedance to these currents. This is the effect we are trying to maximise.

4. The effect of impedance

As with any other component, when a ferrite is placed in circuit it operates between source and load impedances. A quick glance at the equivalent circuit (Figure 3, which also shows parasitic capacitance, which we'll come to later) shows that maximum attenuation due to the simple impedance divider will occur when Z_S and Z_L are low. For example, if Z_S and Z_L are 10 ohms and the ferrite impedance at a given frequency is 100 ohms, the total attenuation (with versus without ferrite, assuming purely resistive impedances) is

Figure 3 A ferrite component between source and load impedances



$$A = 20\log_{10} [(10+10)/(10+100+10)] = -15.6dB$$

but if the circuit impedances are 200 ohms, the attenuation becomes

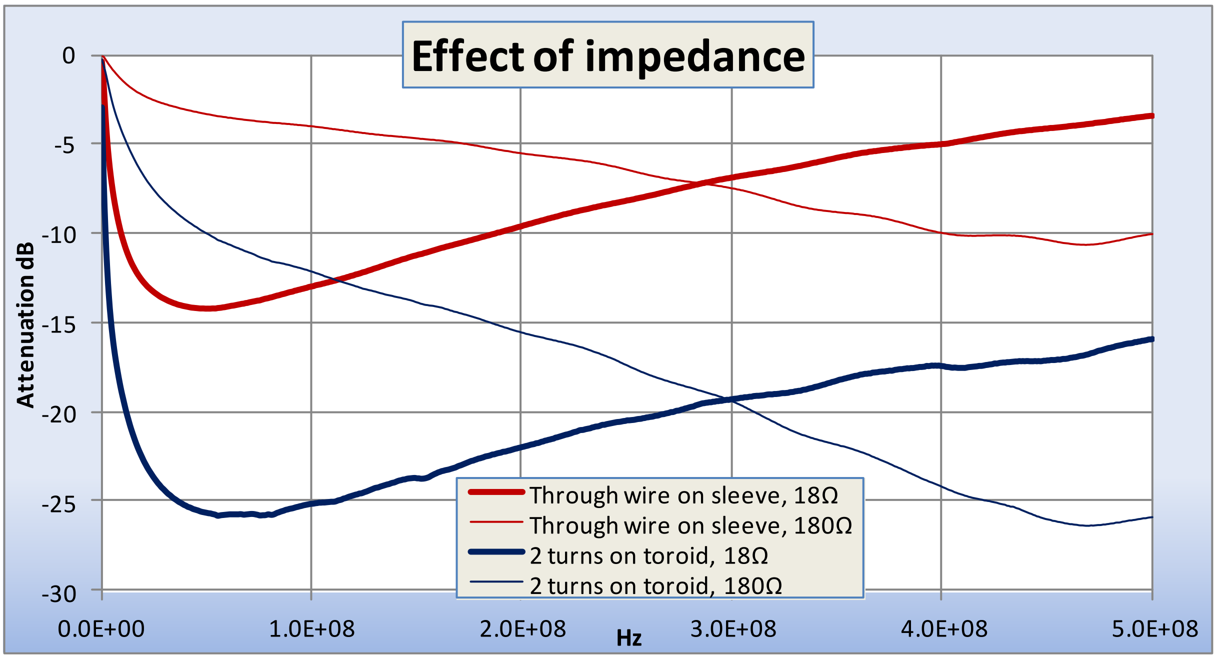
$$A = 20\log_{10} [(200+200)/(200+100+200)] = -2dB$$

For cable interfaces, low source impedance means that the ferrite should be applied adjacent to a capacitive filter to ground or to a good screen ground connection. (See also capacitive effects later.) For open-ended or long cables, the RF common-mode load impedance varies with frequency and cable length and termination: a quarter wavelength from an open circuit, the impedance is low, a few ohms or tens of ohms; a quarter wavelength from a short circuit, the impedance is high, a few hundred ohms. Note that this is the *common-mode* impedance with respect to an external ground: it is unrelated to the cable's internal characteristic impedance or any differential circuit terminations.

Therefore, the location of a ferrite sleeve along a cable determines its effectiveness: if a cable's common mode impedance is mismatched – which it usually is – then a standing wave exists along the cable and its impedance varies with position, from low impedance at points of high current to high impedance a quarter wavelength further along. Placing a ferrite at a position of low impedance is more effective than at a high impedance node. But this is not very helpful, since the node positions change with frequency, so it's most usual to place a ferrite near to the equipment end of a cable, on the assumption that this will be a low impedance point over a wide frequency range. This assumption does depend on the nature of the equipment and the design of its interface; large, metallic equipment enclosures with screened cables will certainly show a low impedance, while small, plastic-housed products with unscreened interfaces using series chokes will be much higher, and will probably not benefit from a cable ferrite at all.

As an average value for the cable impedance, 150 ohms is typical. Ferrite sleeve impedances rarely exceed 200-300 ohms, and consequently the attenuation that can be expected from placing a ferrite on an open cable is typically 6-10dB, with 20 dB being achievable at certain frequencies where a severely mismatched cable shows a low impedance. Figure 4 shows the actual attenuation for two types of core at two different circuit impedances (see the appendix for a description of how these plots were taken: the apparent anomaly, by which the low impedance termination is *worse* than high impedance at the higher frequencies, is due to the significant pre-existing attenuation of the un-ferrited straight wire, which has been normalised out).

Figure 4 The effect of impedance



5. Choosing and using

Size and shape

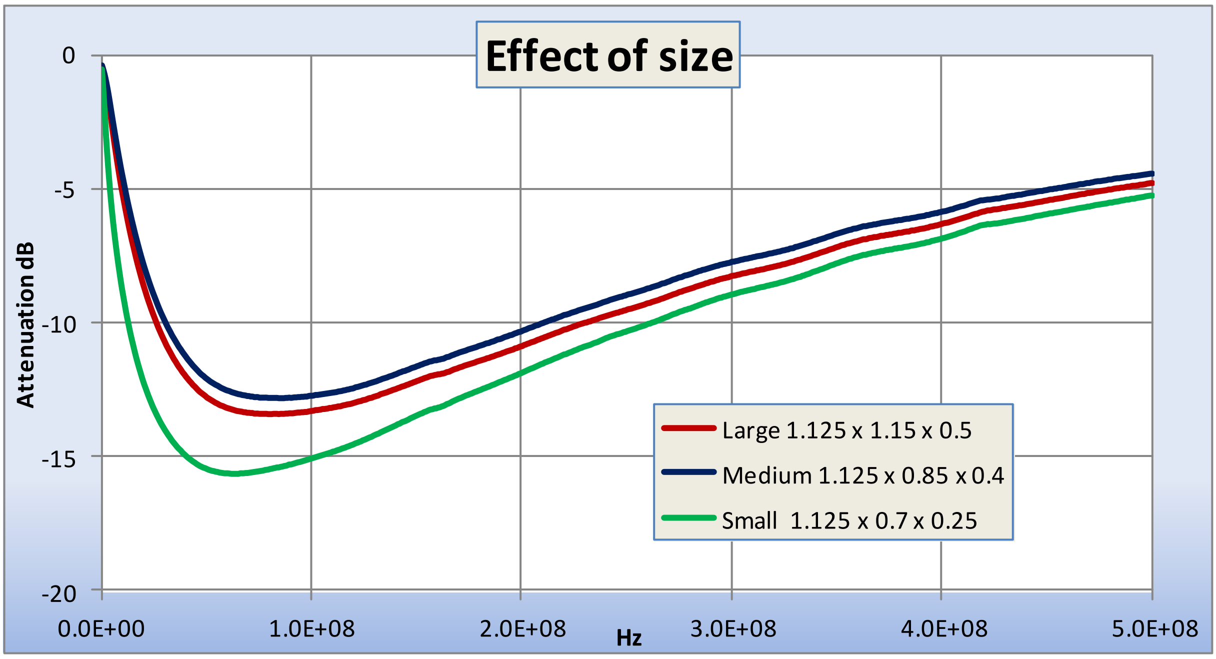
There are two rules of thumb in selecting a ferrite sleeve for highest impedance:

- where you have a choice of shape, longer is better than fatter;
- get the maximum amount of material into your chosen volume that you can afford.

The impedance for a given core material is proportional to the log of the ratio of outside to inside diameter but directly proportional to length[1]. This means that for a certain volume (and weight) of ferrite, best performance will be obtained if the inside diameter fits the cable sheath snugly, and if the sleeve is made as long as possible. A string of sleeves is perfectly acceptable and will increase the impedance *pro rata*, though the law of diminishing returns sets in with respect to the attenuation.

The following curves illustrate this point. Figure 5 shows the attenuation in an 18 ohm circuit for three sizes of clip-on core in a rectangular box, same material, same manufacturer. They are all the same length but of different cross-sectional area. In fact, because of the ratio of OD to ID, the smallest performs the best (as is borne out by the manufacturer's published data). Figure 6 compares attenuation for two parts of virtually the same volume and weight, but different geometries [2].

Figure 5 Comparing three different sizes of clip-on core, same material, straight through wire in 18 ohms

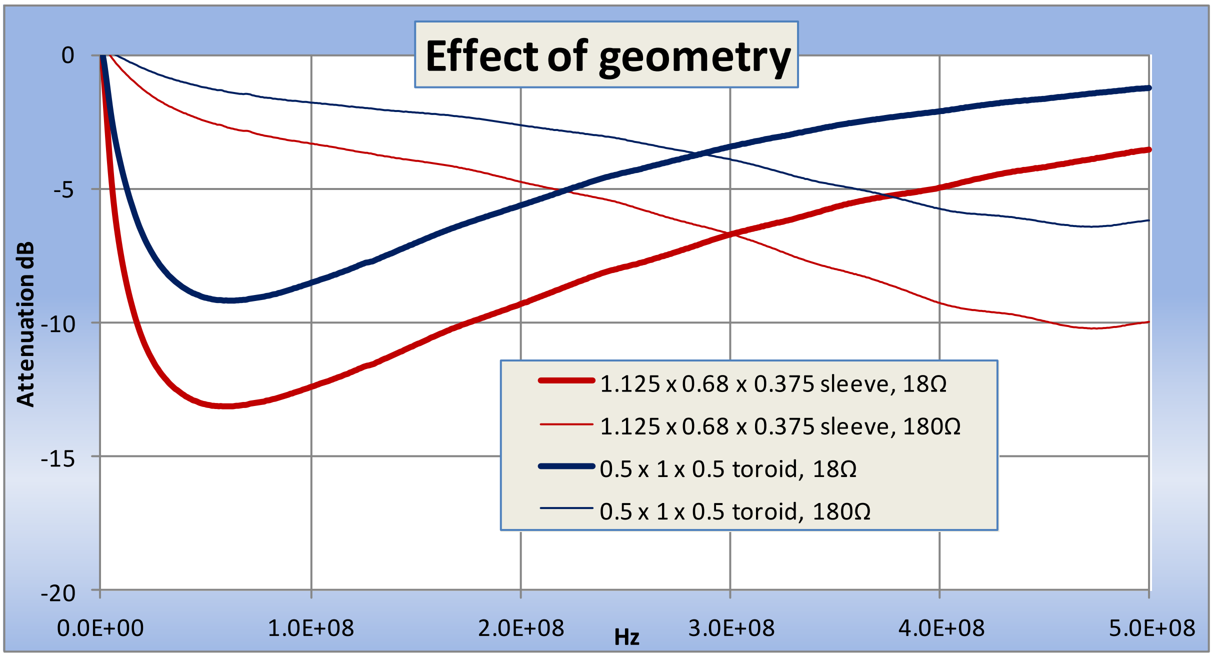


log(OD/ID) ratios: small, 0.447; medium, 0.327; large, 0.362

[1] See Fair-Rite Products Technical Information, "How to choose ferrite components for EMI Suppression", https://www.fair-rite.com/wp-content/uploads/2015/08/CUP-Paper.pdf

[2] The ferrite part dimensions are described in the graphs in the order LENGTH x OUTER DIAMETER x INNER DIAMETER, in inches.

Figure 6 Comparing equal volumes, same material, different geometries, through wire



Number of turns

Inductance can be increased by winding the cable more than one turn around a core; theoretically the inductance is increased in proportion to the square of the number of turns, and at the low frequencies this does indeed increase the attenuation. But it is usual to want broadband performance from a ferrite suppressor and at higher frequencies other factors come into play. These are:

- the core geometry already referred to; the optimum shape is long and snugly-fitting on the cable, and this does not lend itself to multiple turns
- inter-turn capacitance, which appears as a parasitic component across the ferrite impedance and which reduces the self resonant frequency of the assembly.

A toroid rather than a sleeve is preferable for multiple-turn implementations. The main effect of multiple turns is to shift the frequency of maximum attenuation downwards. It will also increase the value of maximum attenuation achieved. The source and load impedances are critical in determining the effect, as they determine the impact of parasitic capacitance. The following two graphs in Figure 8 illustrate this.

Notice that with more turns, the impact of the turns spacing becomes significant, more so as the frequency increases. The photo in Figure 7 illustrates what is meant by "close" versus "spread" winding. While there is little difference at the low frequency end, at higher frequencies it is helpful to keep the turns wide apart on the core.

Figure 7 The two versions of the 4-turn winding

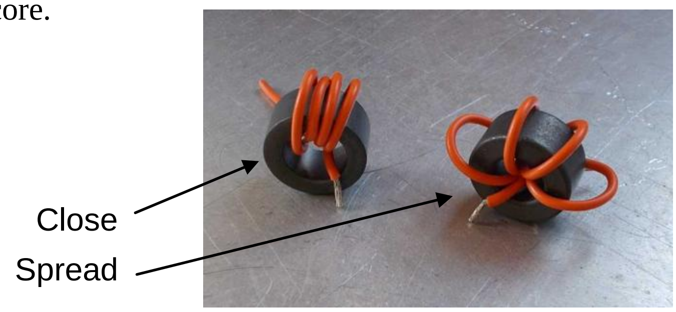
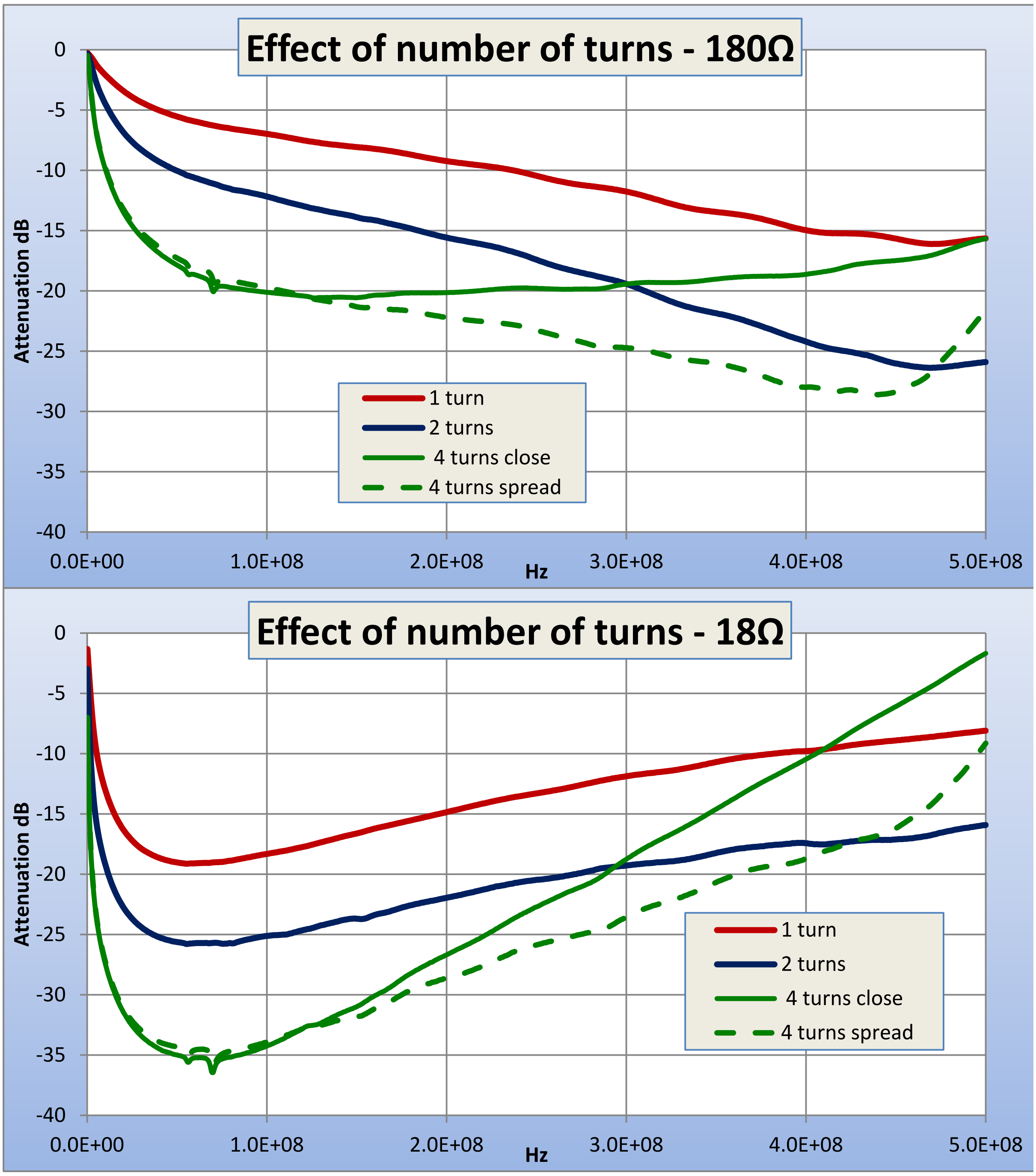


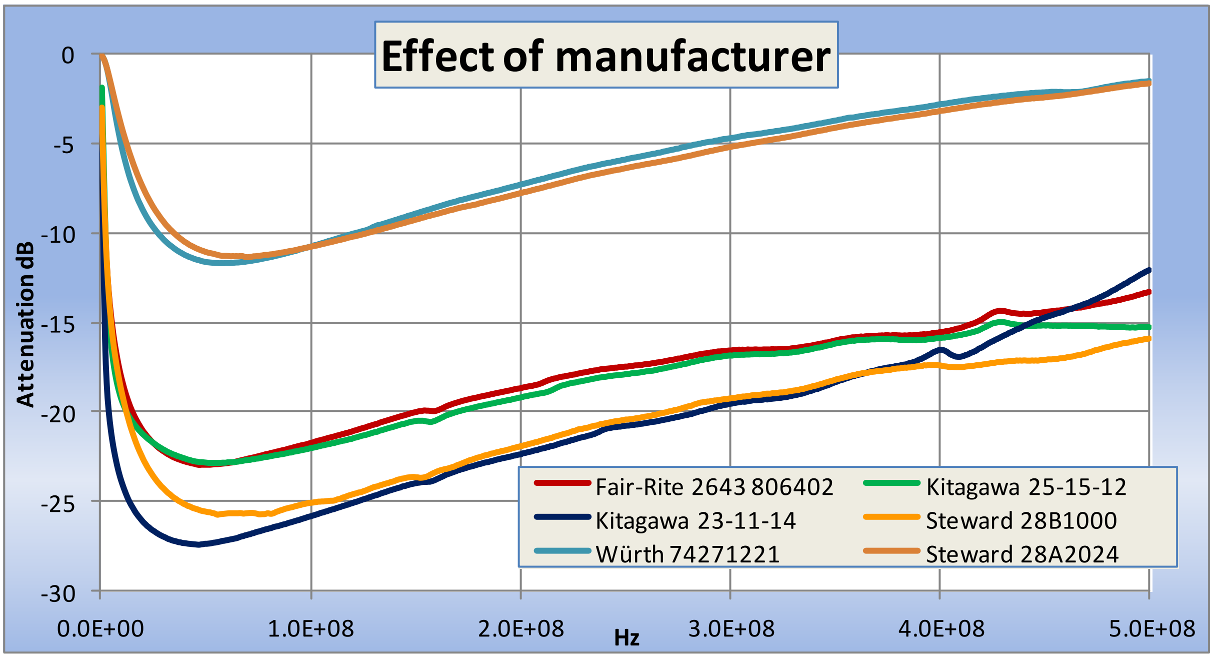
Figure 8 Effect of multiple turns on a 0.5" x 1" x 0.5" toroid



Difference between manufacturers

Generally, there is not a great deal of difference between equivalent-sized parts produced by different manufacturers. Several common sizes are now multi-sourced with similar material compositions and obviously it is worth looking for these in preference to custom or unusual sizes. There may be a maximum of 2-3dB difference at some frequencies between suppliers, but whether this makes it worth preferring one supplier over another is debatable. Figure 9 shows the degree of difference that might be expected.

Figure 9 Comparing different manufacturers, in 18 ohms



Dimensions: Würth – Steward, 1.125" L x 1.0" W x 0.5" ID rectangular clamp, through wire
2 turns on toroid: Kitagawa 23-11-14, 14mm L x 23.5mm OD x 11mm ID
Steward 28B1000, 12.5mm L x 25mm OD x 12mm ID
Fair-Rite 2643-806402, 12.5mm L x 25mm OD x 15mm ID
Kitagawa 25-15-12, 12mm L x 25mm OD x 15mm ID

Note that some of the parts used in these experiments were quite old and are no longer available as their specific part number; but it is interesting to see that the comparison between a brand new Würth part and a decades-old Steward of exactly the same dimensions does show identical performance, suggesting that once the ferrite material characteristics have been optimised (as can be seen from each manufacturer's generic material curves), any part of the same size and shape will do.

6. Secondary effects

Capacitance

Because a ferrite material is in fact a ceramic, it has a high permittivity as well as permeability, and hence will increase the capacitance to nearby objects of the cable on which it is placed. This property can be used to advantage especially within equipment. If the ferrite is placed next to a grounded metal surface, such as the chassis, an R-L-C filter is formed which uses the ferrite both as a resistive inductor and as a distributed capacitor. This will improve the filtering properties compared to using the ferrite in free space. For best effect the cable should be against the ferrite inner surface and the ferrite itself should be flat against the chassis so that no air gaps exist; this can work well with ribbon or flexi cable assemblies. The graph in Figure 10 (taken in a 150 ohm system, and extending up to 1GHz) shows the improvement for the geometry depicted. Around 5dB can be gained at the higher frequencies, although this is probably the best case.

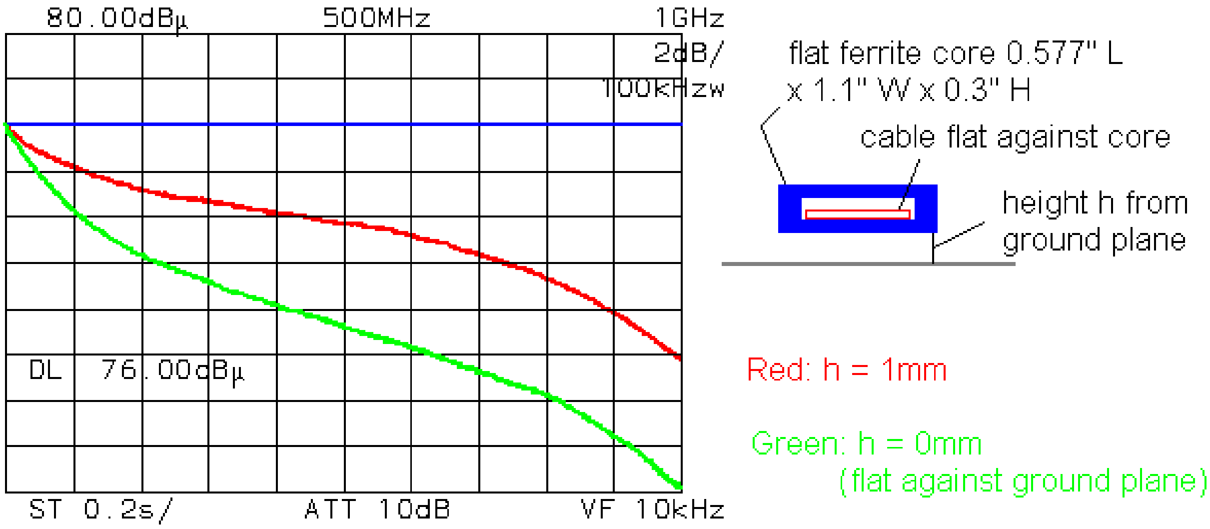


Figure 10 Capacitive effect on a flat cable ferrite against a ground plane

Leakage resistance

A ferrite material is also slightly conductive. This is rarely a disadvantage unless you intend to place the ferrite over a bare conductor, in which case you should be aware of the possible hazards, such as leakage in high-impedance circuits, it might bring. Volume resistivities of 10^5 to 10^8 ohm-cm are typical with 10^9 achievable.

Saturation

As with other types of magnetic material, ferrite suppression cores can saturate if a high level of low-frequency current is passed through them. At saturation, the magnetic material no longer supports an increase in flux density and the effective permeability drops towards unity, so the attenuation effect of the core disappears. The great virtue of the common-mode configuration is that low frequency currents cancel and the core is not subjected to the magnetic field they induce, but this only happens if the core is placed around a cable carrying both forward and return currents. If you must place a core around a single conductor (such as a power supply lead) or a cable carrying a net low frequency current, be sure that the current flowing does not exceed the core's capability; it is usually necessary to derive this from the generic material curves for a particular core geometry.

7. Ferrite diagnostics

A very common situation arises at the test house when a product fails a radiated emissions test at some frequency or frequencies, and the test engineer rummages in the ferrite samples bin, hands one to the customer and says “here, try one of these”. With luck, clipping it over an offending cable will bring the emission below the limit line and the customer gets their “pass” report, albeit with a note to say that this particular ferrite is necessary on that cable.

Hopefully, this paper will have demonstrated that it’s not really luck that counts; the needed attenuation could be predicted if:

- The cable, or cables, causing the emissions failure, can be positively identified;
- The common-mode impedance along the cable can be appreciated.

Sadly, neither of these conditions are usually known in advance to the product’s design engineer, and so the application of ferrite clamps proceeds on a suck-it-and-see basis. But some diagnostic information can be gained from these trials. Firstly, it is usually the case that radiated emissions are dominated by cable coupling up to about 200MHz, but the cable path decreases in significance above this. Trying to cure radiated emissions with cable ferrites above, say, 300MHz is unlikely to succeed.

Below this frequency, and down to maybe 50MHz, then a ferrite *will* give a reduction in emissions *if* the cable on which it is fitted is actually the one dominating the emissions profile, and if its common mode impedance at the relevant position is significantly lower than the impedance provided by the ferrite. If either of these conditions is not met, the ferrite won't help much, and this gives a form of negative diagnostic, saying that you should try another cable or another approach. But at the same time, don't give up on what you tried just because "it didn't work": if, later, you find the dominant path and deal with it, it may still be necessary to deal with the original cable which is also emitting too much, but to a lesser extent.

At lower frequencies, be aware that a ferrite will be less effective anyway, unless you can wind multiple turns around a toroidal core: see Figure 8 for a hint as to how helpful this might be.

References

Various suppliers of suppression ferrites are:

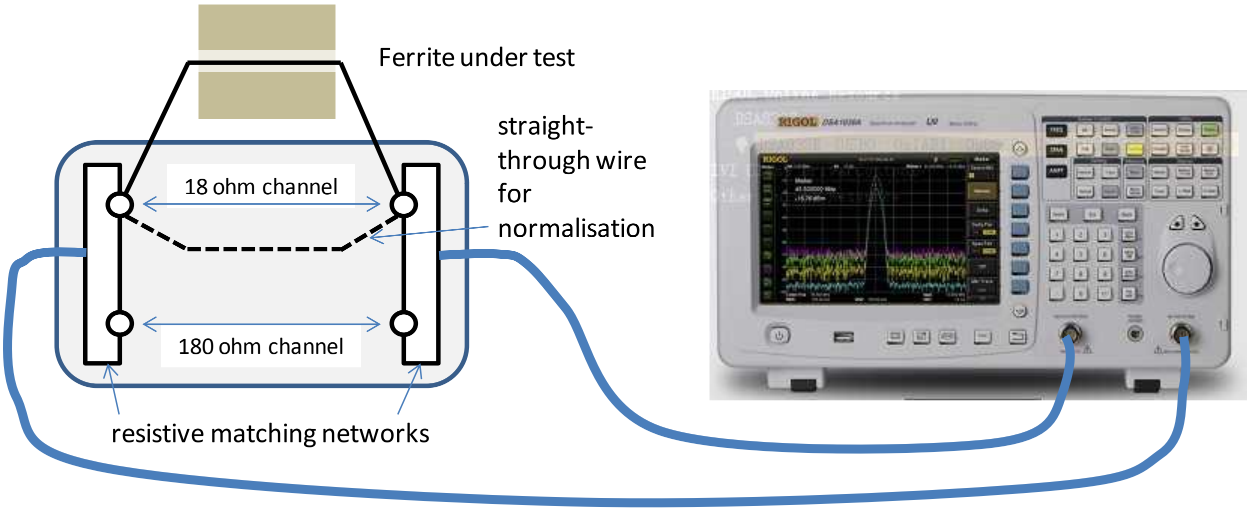
- Würth (Germany)
- TDK (Japan/US)
- Fair-Rite (US)
- Kitagawa (Japan/Germany)
- Ferroxcube (Netherlands/Taiwan)

Although there are several other suppliers of ferrite products than those mentioned, most of these do not carry a wide range of HF suppression ferrite sleeve components.

Appendix: ferrite test set-up

The plots shown in this tutorial used a Rigol spectrum analyser and tracking generator with an impedance conversion jig as shown in the diagram below. This jig allowed different ferrites to be evaluated with source and load impedances of either 18 ohms or 180 ohms. Resistive matching networks were used to convert from the standard 50 ohms of the spectrum analyser to the required impedance. These values allow a similar straight-through attenuation in each case, and were chosen as follows:

- 18 ohms represents the lowest likely common mode circuit impedance to be found in most applications, usually within equipment, and shows up the ferrite to its best effect;
- 180 ohms represents the common-mode impedance of cables (see for instance IEC61000-4-6 or CISPR16-1-2, which mandate 150 ohms) and shows the lesser effect more likely to be achieved when putting ferrite sleeves on external cables.



Interpreting the plots

All plots are a linear frequency scan from 0 to 500MHz. The reported level was normalised against a straight-through connection to take out the frequency-dependent effects of the jig. Although these are not themselves significant, the effect of a straight-through 2" length of wire has to be removed since it is against the "attenuation" of this wire that the ferrite performance is judged. The self-inductance of this wire is around 50nH which at 500MHz is nearly 160 ohms; this puts in a significant amount of attenuation in an 18 ohm system which must be normalised out. This explains why, at the higher frequencies the 18 ohm system actually appears worse than the 180 ohm system; the ferrite isn’t increasing the wire’s own attenuation so much.

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