Using ferrites for interference suppression

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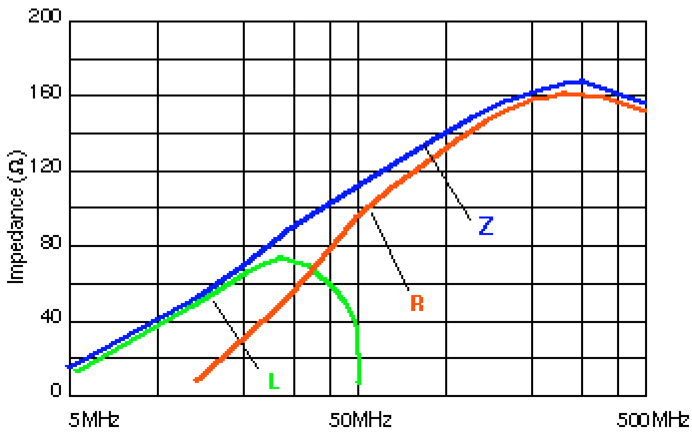
1. Introduction

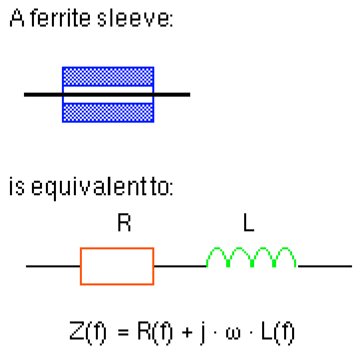
One of the most used yet least understood techniques for reducing both incoming and outgoing RF interference is the application of ferrite sleeves to cables and at interfaces. This tutorial is meant to shed some light on the use of ferrites, and also presents some comparative frequency domain measurements 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 straight wire the self-inductance is typically 20nH per inch. Placing a magnetically permeable material around the conductor increases the flux density for a given field strength and therefore increases the inductance.

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 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.





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 "go" current in each circuit pair is cancelled by the field produced by its equal and opposite "return" current, provided that the two conductors are adjacent. 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 *no effect* on the differential mode signals carried within it.

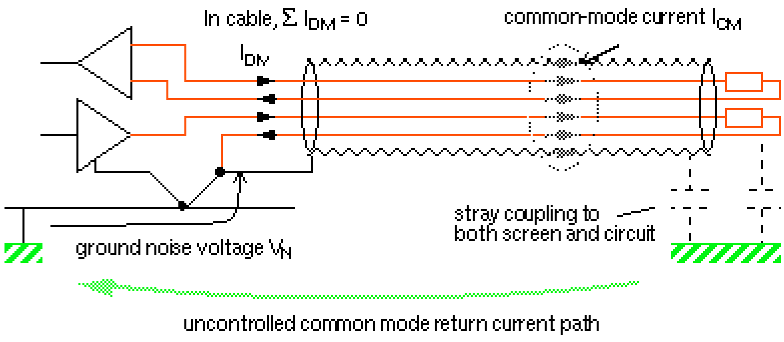
Common mode

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

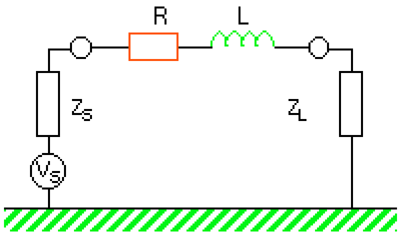
- ground-referred noise at the point of connection, which may have nothing to do with the signal(s) carried on the cables, or
- imbalance of the impedance to ground of the various signal and return circuits, so that part of the signal current returns through paths other than the cable harness.

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. Also, incoming RF or transient interference currents are invariably 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 inserted around the cable will *increase* the cable's local impedance to these currents.



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 (above) 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) is

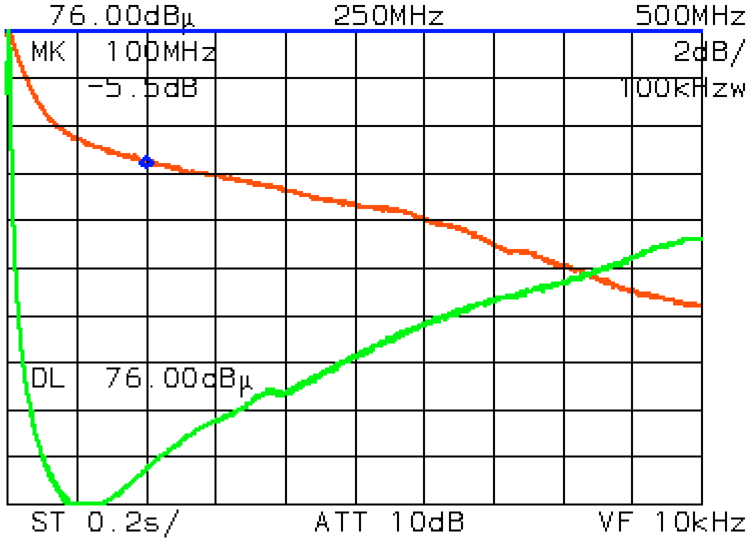
$$A = 20\log_{10} [(10+10)/(10+100+10)] = -15.6\text{dB}$$

but if the circuit impedance is 200 ohms, the attenuation becomes

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

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 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. (This property of cables is well known to antenna designers but looks like magic to the rest of us.) Since you do not normally know the length and layout of any cable that will be attached to a particular interface, and since the impedance is frequency dependent anyway, it is usual to take an average value for the cable impedance, and 150 ohms has become the norm. (Note that this is the *common-mode* impedance: it has nothing to do with the cable's characteristic impedance or any differential circuit terminations.)

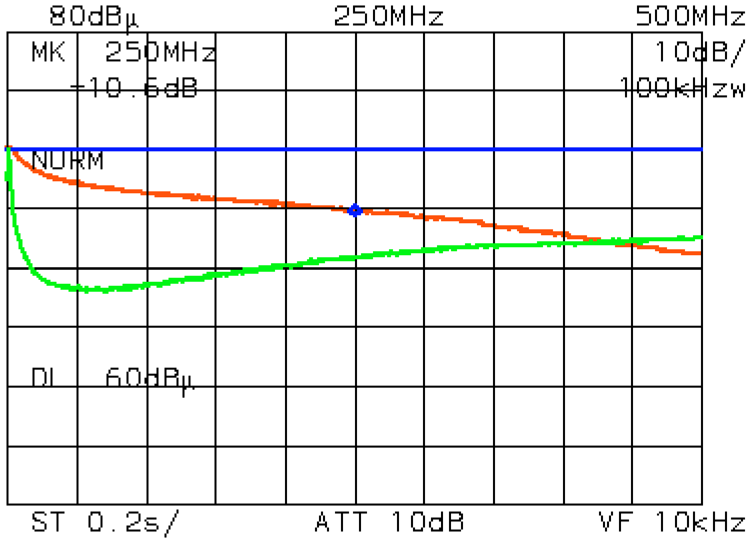
Ferrite impedances rarely exceed 2-300 ohms, and consequently the attenuation that can be expected from placing a ferrite on an open cable is typically 6-10dB, with 20 dB being achievable at certain frequencies where the cable shows a low impedance. The following plots show the actual attenuation for two types of core at two different circuit impedances (see the appendix for a description of how these plots were taken). Note that the two plots have different vertical scales (2dB/div versus 10dB/div).



Round sleeve core, 1.125" x 0.56" x 0.25"

Red: 150 ohm

Green: 10 ohm



Toroidal core with 2 turns, 0.5" x 1" x 0.5"

Red: 150 ohm

Green: 10 ohm

5. Choosing and using

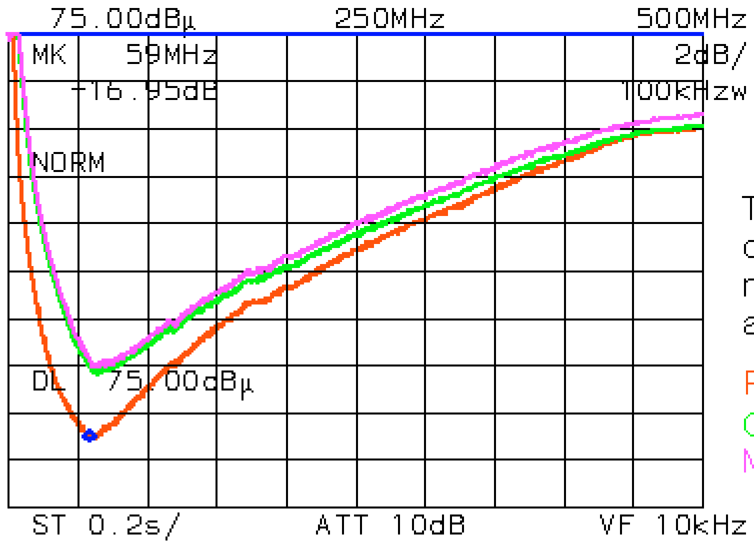
Size and shape

There are two rules of thumb in selecting a ferrite 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.

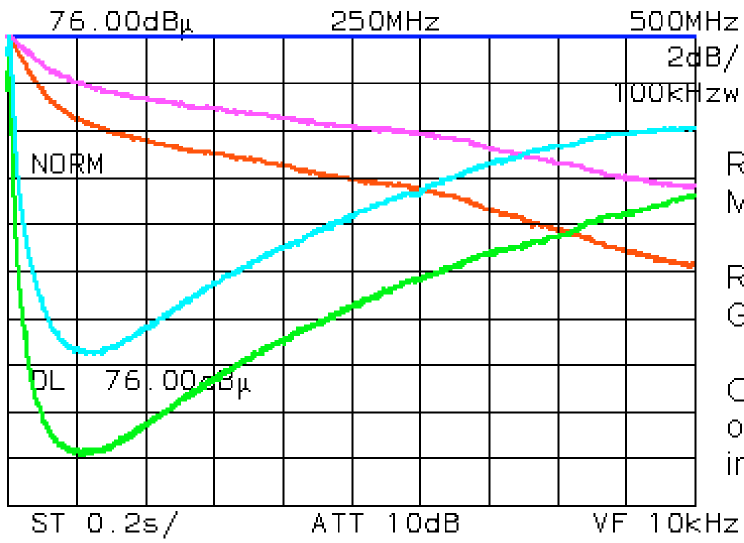
The impedance for a given core material is proportional to the log of the ratio of outside to inside diameter but directly proportional to length. This means that for a certain volume (and weight) of ferrite, best performance will be obtained if the inside diameter fits the cable sheath snugly, and if 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. The first shows the attenuation in a 10 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, the smallest performs the best (as is borne out by the manufacturers' published data). The second graph compares attenuation for two parts of the same volume, but different geometries.



Three square clip-on cores from the same manufacturer, 1 turn in a 10 ohm circuit:

Red 1.25" x 0.7" x 0.25"
Grn 1.25" x 1.15" x 0.5"
Mag 1.25" x 0.85" x 0.4"



Red, green: 1.125" x 0.68" x 0.4"
Mag, cyan: 0.5" x 1" x 0.5"

Red, mag: 150 ohms
Green, cyan: 10 ohms

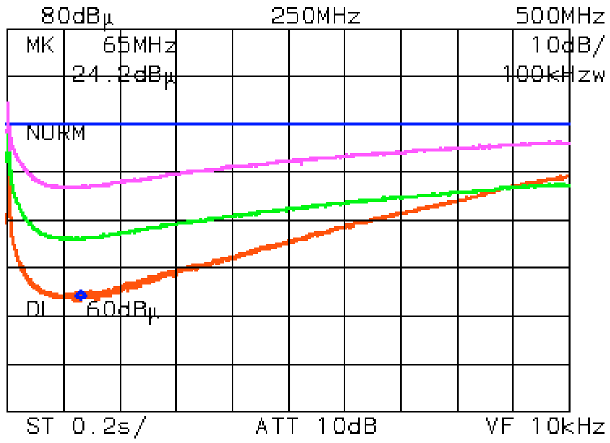
Comparing two geometries of equal volumes in two impedances

Number of turns

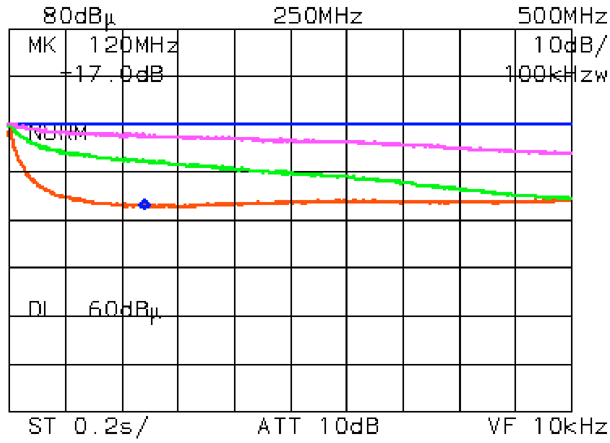
Inductance can be increased by winding the cable more than one turn around a core; theoretically the inductance is increased proportional to the square of the number of turns, and at the low frequencies this does indeed increase the attenuation. But it is usual to want broadband performance from a ferrite 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
- more importantly, inter-turn capacitance, which appears as a parasitic component across the ferrite impedance and which reduces the self resonant frequency of the assembly.

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 but not by as much as hoped. The source and load impedances are critical in determining the effect: the lower the impedances, the less the effect of parasitic capacitance. The following two graphs illustrate this.



10 ohm system

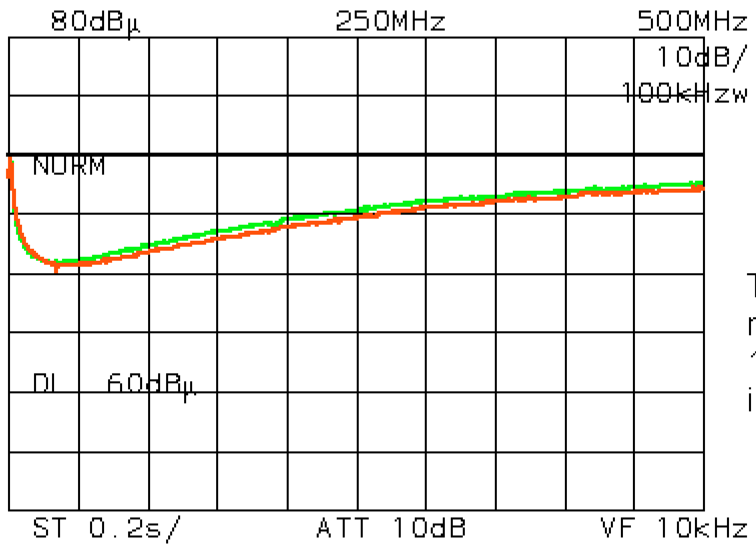


150 ohm system

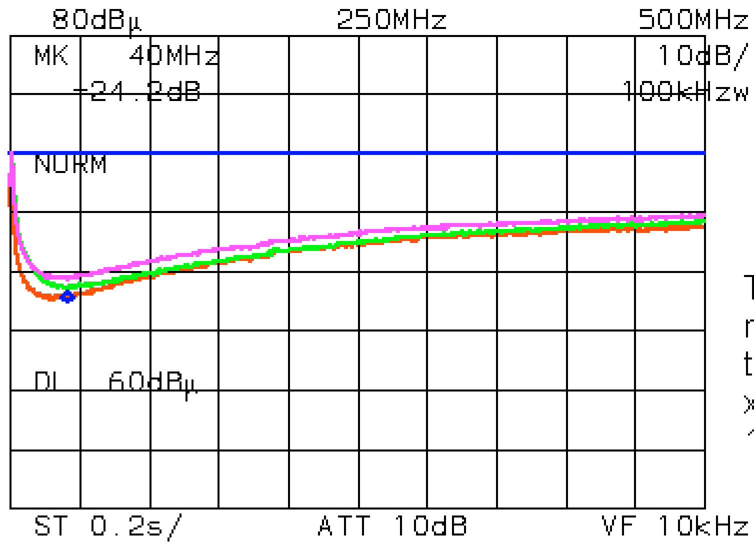
Red: 4 turns Green: 2 turns Mag: 1 turn Core: 0.57" x 0.375" x 0.2"

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. The following couple of graphs show the degree of difference that might be expected.



Two different manufacturers, 1.1" x 0.6" x 0.25" in a 10 ohm circuit

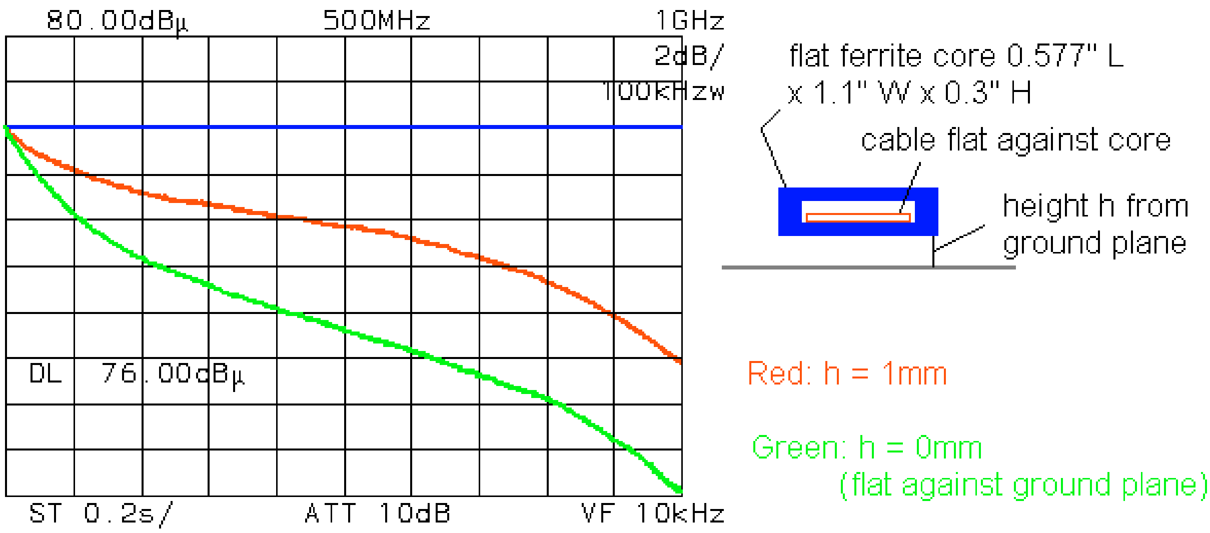


Three different manufacturers, 2 turns on core 0.5" x 1.0" x 0.5" in a 10 ohm circuit

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 L-C filter is formed which uses the ferrite both as an 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 below (taken in the 150 ohm system) shows the improvement for the geometry depicted. Around 5dB can be gained at the higher frequencies (note that this plot extends up to 1GHz), although this is probably the best case.



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 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 go- 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.

References

Various suppliers of suppression ferrites are:

- TDK (Japan/US)
- Fair-Rite (US)
- Steward (US)
- Panasonic (Japan)
- Murata (Japan)
- Kitagawa (Japan/Germany)
- Philips (Holland/UK)
- MMG-Neosid (US/UK)

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.

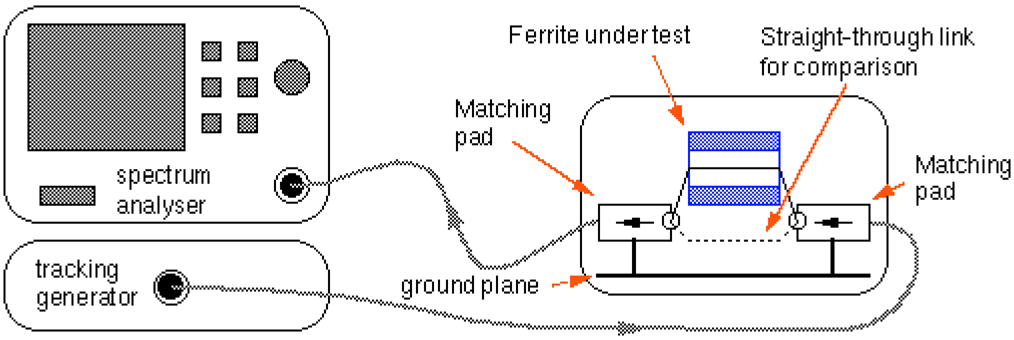
The comparative plots were mostly done using Steward parts in their 28 material, kindly supplied as an engineering kit by their UK distributor Kemtron of South Woodham Ferrers, tel 01245 325555, fax 01245 325590.

Much of the information used in this tutorial derives from the application handbooks and data published by Steward and Fair-Rite.

Appendix: ferrite test set-up

The plots shown in this tutorial used an Advantest R4131 spectrum analyser and tracking generator with an impedance matching jig as shown in the diagram below. This jig allowed different ferrites to be evaluated with source and load impedances of 10 ohms or 150 ohms. Resistive matching networks were used to convert from the standard 50 ohms of the spectrum analyser to the required impedance. The impedances were chosen as follows:

- 10 ohms represents the lowest likely circuit impedance to be found in most applications, usually within equipment, and shows up the ferrite to its best effect;
- 150 ohms represents the common-mode impedance of cables (see for instance IEC1000-4-6 or CISPR16-1) and shows the 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 vertical scale is either 10dB per division or 2dB per division as shown in the top right corner. The blue line across the trace shows the 0dB reference level against which the ferrite attenuation is measured. This 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 1.5" 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 30nH which at, say 250MHz is 47 ohms; this puts in a significant amount of attenuation in a 10 ohm system which must be normalised out.

The ferrite part dimensions are described in the diagrams in the order LENGTH x OUTER DIAMETER x INNER DIAMETER.

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