Ferrites for Interference Suppression

The lossy, wideband nature of ferrites make them effective and reliable interference suppression devices.

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INTRODUCTION

Larger numbers of electronics, digital circuitry and switched-mode power supplies have made interference suppression a major design consideration. The concern is repeatedly reflected in stricter regulations.

Soft ferrites are ceramic, ferromagnetic materials widely used for interference control. Their lossy, wideband nature results in reliable suppression characteristics. Soft ferrites can be characterized according to composition, magnetics and applications. Soft ferrites consist of a mixture of iron oxide, Fe_2O_3, with other metal oxides. Usually these metals are manganese-zinc and nickel-zinc. Design considerations that determine material choice are signal conditions, such as frequency and bias current, and ambient conditions such as temperature.

Being ferromagnetic materials with a high electrical resistivity, soft ferrites do not need insulation to reduce eddy currents, and thus they maintain high permeability up to RF frequencies. Furthermore, the value of impedance and the degree of saturation through a bias current can be calculated easily from a reference core of the same material.

PRODUCTION PROCESS

The typical soft ferrite production process consists of four steps: powder preparation, formation, sintering, and finishing. First, raw materials are weighed, mixed and milled to a fine powder. The powder is then pre-sintered and pulverized again. The product shape is made by either pressing the powder directly or by continuously extruding it through a nozzle and then cutting it at the desired length. The products are then sintered at temperatures exceeding 1000° C in air (moving belt kiln) or in a controlled atmosphere (stationary kiln). During sintering they shrink approximately 20% linearly (pre-sintering included) and convert to ferrite. The finishing stage includes mechanical operations such as grinding, coating, and wiring. The last steps are final inspection and packing.

MATERIAL PROPERTIES AND APPLICATIONS

In most electronic devices an inductive suppression component is connected in series with the interference source. The regular signal is normally either a dc supply or a 60-Hz mains for which an inductor only presents a small copper resistance. At RF frequencies the inductor shows a high impedance which suppresses unwanted interference. The resulting voltage over the load impedance will be lower than the voltage without the suppression component. The ratio of the two is the insertion loss (Figure 1).

The insertion loss is expressed logarithmically:

$$IL = 20 \cdot \log_{10} (E_0/E) = 20 \cdot \log_{10} \left|(Z_g + Z_l + Z_s) / (Z_g + Z_l)\right| \ (\text{dB})$$

where E is the load voltage with the inductor, E_0 is the load voltage without the inductor, and Z is the impedance.

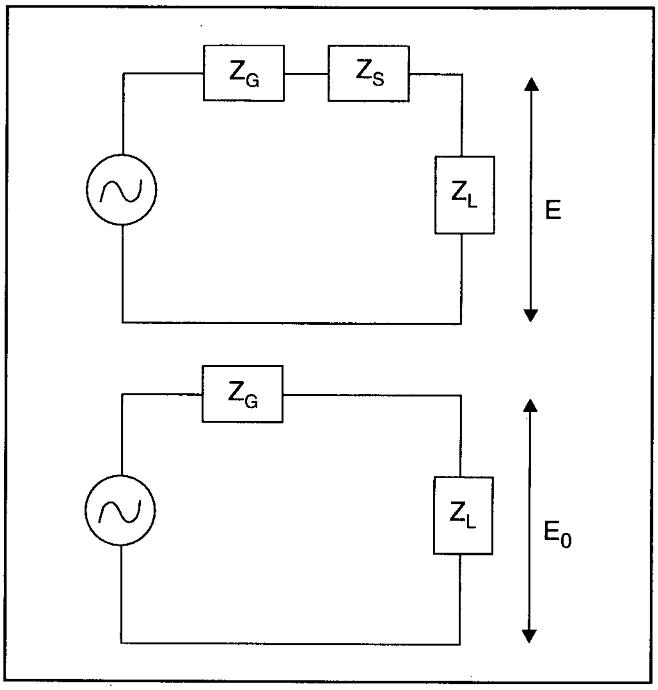


Figure 1. *Insertion Loss of an Inductor.*

The decibel as a unit of measurement seems acceptable because interference levels are expressed in decibels, but it does have limitations. First, insertion loss depends on source and load, so it is not a pure product parameter like impedance. Second, in the actual application, source and load will not be a 50-ohm fixed resistance. They might be reactive, frequency-dependent and quite different from 50 ohms. Therefore, insertion loss can be considered a standardized parameter for comparison, but it will not directly predict the attenuation in the application.

At low frequency, a ferrite inductor is a low-loss, constant self-inductor. Interferences occur at elevated frequencies and there the picture changes. Losses start to increase and at a certain frequency, permeability drops rapidly to zero and the impedance becomes completely resistive. At higher frequencies it even becomes capacitive with losses. While for classic applications the operating frequency should stay well below the resonance, effective interference suppression is achieved up to much higher frequencies. The impedance peaks at the resonance frequency and the ferrite is effective in a wide frequency band around it.

At resonance and up, the impedance is largely resistive, which is a favorable characteristic of ferrites. First, a low-loss inductance can resonate with a capacitance in series (positive and negative reactance), leading to almost zero impedance and interference amplification. Resistance can't resonate and is reliable regardless of source and load impedances.

Second, a resistance dissipates interfering signals rather than reflecting them to the source. Small oscillations of high frequency can damage semiconductors or negatively affect circuit operation and therefore it is preferable to absorb them.

Third, the shape of the impedance curve changes with the material losses. A lossy material will show a smooth variation of impedance with frequency and a real wideband attenuation. Interference often must be suppressed over a wideband spectrum.

IMPEDANCE CONCEPT

MATERIAL

The impedance curve can be translated to a pure material curve known as the complex permeability curve (Figure 2). Since impedance consists of a reactive and a resistive part, permeability should also have two parts to represent this. The real part corresponds to the reactance, which is positive for an inductance and negative for a capacitance, and the imaginary part corresponds to the losses.

$$Z = j\omega \cdot (\mu' - j\mu'') \cdot L_O = \omega \cdot \mu'' \cdot L_O + j\omega \cdot \mu' \cdot L_O$$

$$Z = R + jX \rightarrow R = \omega \cdot \mu'' \cdot L_O \cdot X = \omega \cdot \mu' \cdot L_O$$
$$(\omega = 2 \cdot \pi \cdot f)$$

$$Z = \sqrt{R^2 + X^2} = \omega \cdot L_O \sqrt{\mu'^2 + \mu''^2}$$

where L_O is the inductance if initial permeability were equal to 1:

$$L_O = \mu_O \cdot n^2 \cdot A_e / l_e \; (\mu_O = 4\pi \cdot 10^{-7} = 1.2566 \cdot 10^{-6} \text{ [H/m]})$$

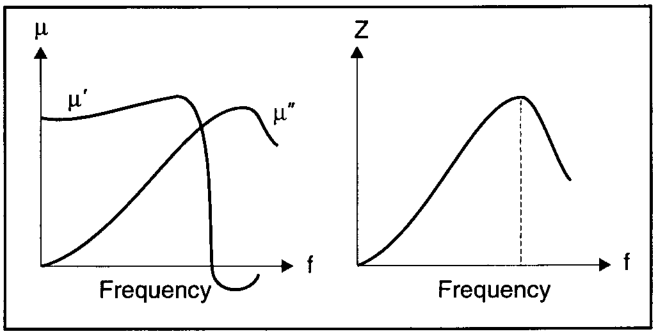


Figure 2. *Complex Permeability and Impedance.*

CORE SIZE

The selection of a suppression product is a two-step process. First, the material choice corresponding to the interference frequencies must be determined. Then the right core size and turns for the impedance level required must be determined. The simplest way to calculate is to use the impedance curve of a reference core of the same material. Calculation from complex permeability is another possibility, but it is more troublesome. Two factors must be corrected: effective magnetic dimensions and turns.

$$Z :: n^2 A_e / l_e \rightarrow Z = Z_O (n^2/n_O^2)(A_e/A_{eO})(l_{eO}/l_e)$$

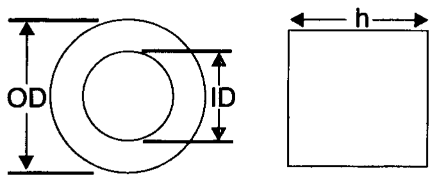
where the parameters with index o correspond to the reference core.

The number of turns, n, is always an integer number. Half a turn geometrically is 1 turn magnetically. For a bead threaded with a single wire, n = 1 turn.

The effective magnetic dimensions A_e (area) and l_e (length) are calculated from geometric dimensions according to IEC Norm 205. For complicated geometries this involves extensive formulas, and suppliers should specify these data in their handbooks. In the case of a cylindrical symmetry (ring core, tubular bead), an analytical formula exists (Figure 3).

BIAS CURRENT

Often a dc supply or 60-Hz mains current is passing through the inductor to facilitate the regular operation of the connected equipment. This current induces a high field strength in the ferrite core, which can lead to saturation. Impedance then decreases along with permeability, especially on the low frequency side.



$$A_e / l_e = h / (2 \cdot \pi) \cdot \ln(OD/ID)$$

OD = outer diameter
ID = inner diameter
h = height

Figure 3. *Ring Core/Tubular Bead.*

The influence of bias current can be calculated rapidly. The induced field strength is directly proportional to the current:

$$H = n \cdot I / l_e$$

Whether this field causes a significant saturation can be seen in the curve of inductance versus bias current. However, this only indicates the decrease of inductance at low frequency. The impedance at high frequency decreases less. Again, impedance can be calculated from reference curves if they show impedance versus frequency with bias current as a parameter. First, bias current is translated to the current that would induce the same field strength in the reference core, which means the same grade of core saturation:

$$I_O = I \ \ (n/n_O) \ \ (l_{eO} / l_e)$$

For a ring core or tubular bead the effective length is:

$$l_e = \pi \cdot \ln(OD/ID) / (1/ID - 1/OD)$$

Now the relative impedance decrease must be the same:

$$Z_{bias} = Z \ \ (Z_{O\,bias} / Z_O)$$

EXAMPLE

As an example, the inductance of a tubular bead will be calculated. Because it has only a single wire, the parasitic "coil" capacitance is small and the frequency behavior is material-determined. The same is usually valid for wideband chokes, which have a few turns (to make more impedance) but have wound-through holes in the core. In this way the distance between the turns reduces parasitic capacitance.

An electric motor (220 V, 0.2 A) injects interference into the mains at a level 10 dB higher than permissible at a frequency of 10 MHz. Looking at the impedance curves of Figures 4a and 4b, it is obvious that the material described by Figure 4a is the best choice. At 10 MHz the motor impedance Z_G was estimated to be 1 ohm and the mains impedance Z_L = 50 ohms (Figure 5). Now the bead impedance Z_S should satisfy the equation and solve the problem.

$$20 \cdot \log_{10} \left| (Z_g+Z_l+Z_S)/(Z_g+Z_l) \right| > 10 \text{ dB}$$

For reasons of simplicity it is assumed that all impedances are practically ohmic. This is certainly the case for the beads within their optimum frequency ranges. Then:

$$\log_{10} (1 + Z_S / 51) > 0.5 \rightarrow Z_g > 110 \text{ ohm}$$

Given the 5 x 2 x 10 mm reference bead in Figure 4a, impedance at 10 MHz is 78 ohms, decreasing to 68 ohms with 0.2 A bias current. If the inner diameter is fixed by the wire, then the necessary impedance can be achieved in two ways.

Option 1: Increasing Height
h > 110/68 x 10 = 16.2 mm.
Two beads are enough.

Option 2: Increasing Outer Diameter
$\ln(OD/2) > 110/68 \cdot \ln(5/2) \rightarrow OD > 8.82$ mm.
Saturation will be somewhat lower now, because l_e increases.

MATERIAL SELECTION CRITERIA

A number of design parameters should be considered for material selection: the applied signal (frequency and bias current) and ambient conditions (temperature). The influence of the different design parameters is illustrated in Figure 6.

FREQUENCY

The material choice follows from the critical interference frequencies; ideally they should coincide with the ferromagnetic resonance frequency, the top of the impedance curve. According to Snoek's law, this resonance frequency is inversely proportional to the initial permeability, which gives a direct criterion for material choice. The higher the inter-

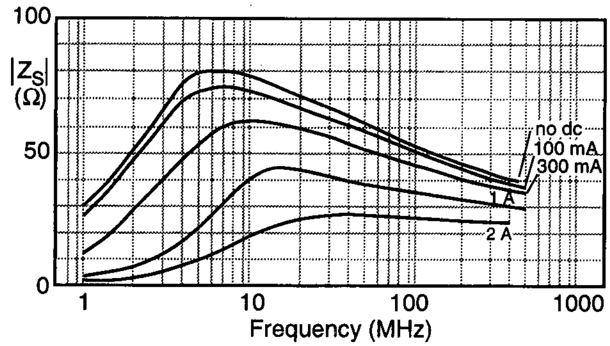


Figure 4a. Impedance as a function of frequency under influence of dc-premagnetization for 3S1 material.

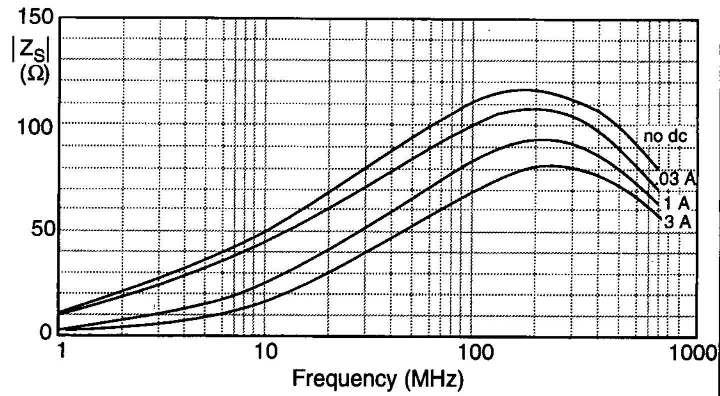


Figure 4b. Impedance as a function of frequency under influence of dc-premagnetization for 4S2 material.

Figure 4. *Impedance Curves of Reference Core 5 x 2 x 10 mm.*

ference frequency, the lower the material permeability. The whole RF spectrum can be covered with a few materials if the right permeability steps are chosen.

BIAS CURRENT

If there is a bias current, then the possible saturation would be verified. If impedance decreases too much, the following remedies exist:

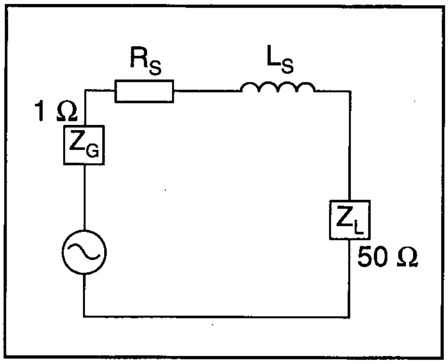


Figure 5. *Example of an Equivalent Circuit.*

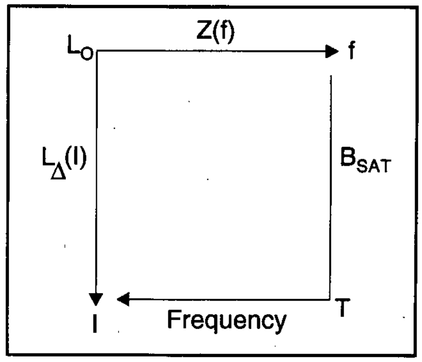


Figure 6. *The Influence of Design Parameters.*

- Choosing lower material permeability or creating a gap (less flux density induced by the same bias current) and more turns (to keep the same impedance value on the low frequency side).

- Choosing larger dimensions (the relevant parameter here is effective magnetic volume $V_e = A_e \times l_e$) and again correcting turns.

The only intrinsic material solution is a higher saturation flux density.

TEMPERATURE

In general, permeability increases with temperature. At a certain point the ferromagnetic properties are lost, i.e., the magnetic domains fall apart. This point is called the Curie temperature of the material. The operating temperature should always stay below the Curie point.

If initial permeability is a lot higher at ambient temperature than at room temperature, resonance frequency is lower (Snoek's law) and the impedance curve will shift to lower frequencies. A material with lower permeability may exhibit improved performance in this case.

The saturation characteristic is also temperature dependent, because saturation flux density decreases with temperature. (At the Curie point it becomes zero.) This means that the core saturation will increase with temperature.

CONCLUSIONS

- Interference suppression regulations are becoming stricter.

- Insertion loss requires high impedance.

- The lossy, wideband nature of ferrite material makes it appropriate for suppression purposes.

- The material is chosen such that the top of the impedance curve is as close as possible to the interference frequency.

- The influence of core size and bias current can be easily calculated, either from a reference core or from complex permeability.

- Ambient temperature must be taken into account in the final application. It can shift the impedance maximum and degrade core saturation.

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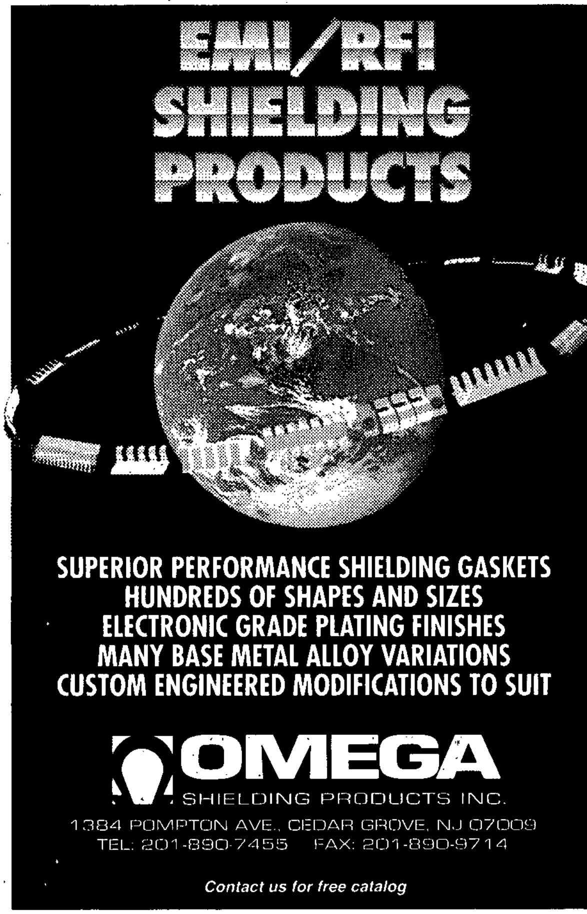

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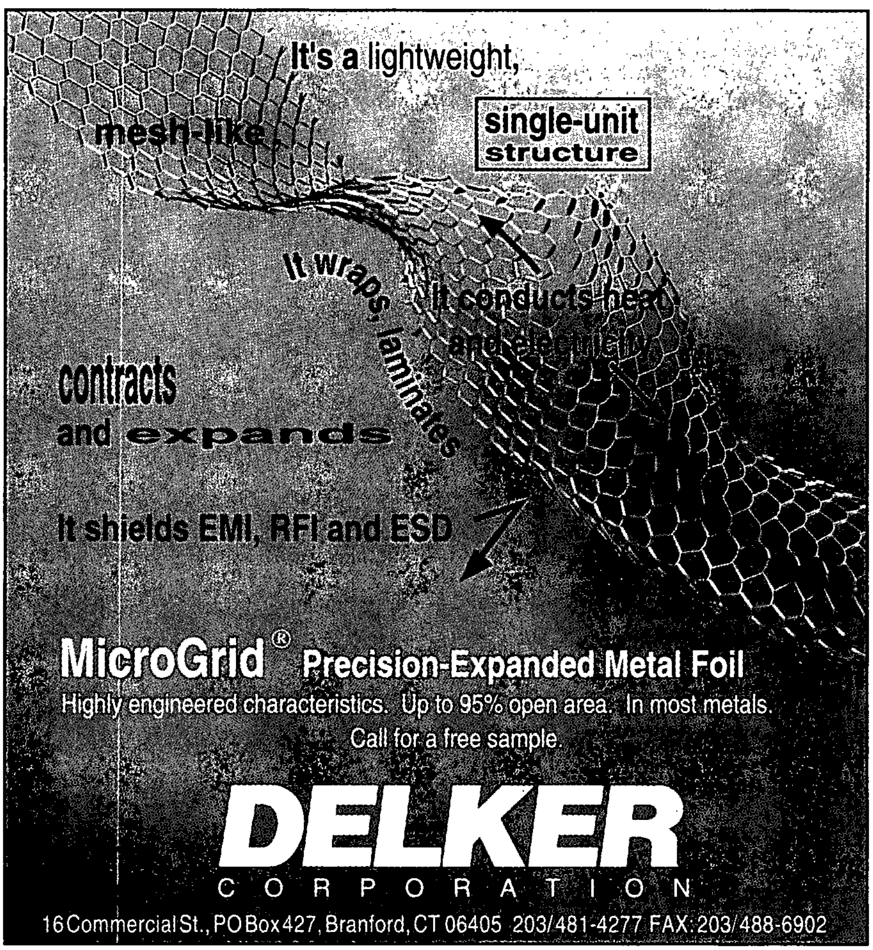

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