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EMC Components

Specifying a Ferrite for EMI Suppression

by Carole U. Parker, Fair-Rite Products



Our past article (see “How to Choose Ferrite Components for EMI Suppression,” *Conformity*, June 2002) was intended to help design engineers optimize the performance of ferrite materials by analyzing the effects of frequency, field strength, temperature and core geometry. In our ideal world, safety (including effect on environment), quality and performance are paramount. However, the cost of the final component (which includes the ferrite) has, in many cases, become the deciding factor.

This article is written as an aide to the design engineer looking for alternative ferrite materials as a means to reduce cost.

A Review of Ferrite Applications

The following are three major applications for soft ferrite:

1. Low signal level
2. Power
3. EMI

The required intrinsic material characteristics and core geometry are dictated by each specific application. The intrinsic characteristics controlling the performance of low signal level applications are permeability (particularly with temperature), low core loss, and good magnetic stability with time and temperature. Applications include high Q inductors, common mode inductors, wideband, matching and pulse transformers, antenna elements for radios and both active and passive transponders. For power applications, the desirable characteristics are high flux density and low losses at the operating frequency and temperature. Applications include switchmode power supplies, magnetic amplifiers, dc-dc converters, power filters, ignition coils, and transformers for battery charging of electrical vehicles.

The intrinsic characteristic that most influences the performance of soft ferrite in suppression applications is the complex permeability, which is directly proportional to the core's impedance. There are three ways to use ferrites as suppressors of unwanted signals, conducted or radiated. The first, and least common, is as actual shields where ferrite is used to isolate a conductor, component or circuit, from an environment of radiated stray electromagnetic fields. In the second application, the ferrite is used with a capacitive element to create a low pass filter that is inductance-capacitance at low frequencies and dissipative at higher frequencies.

The third, and most common use, is when ferrite cores are used alone on component leads or in board level circuitry. In this application, the ferrite core prevents any parasitic oscillations and/or attenuates unwanted signal pickup or transmission that might travel along component leads or interconnected wires, traces, or cables.

In both the second and third applications, the ferrite core suppresses the conducted EMI by eliminating or greatly reducing the high frequency currents emanating from the EMI source. The introduction of the ferrite provides a sufficiently high frequency impedance that results in the suppression of the high frequency currents. Theoretically, the ideal ferrite would provide a high impedance at EMI frequencies, and zero impedance at all other frequencies. In reality, ferrite suppresser cores provide a frequency-dependent impedance, that is, low at frequencies below 1 MHz, and (depending upon the ferrite material) the maximum impedance that can be obtained between 10 MHz to 500 MHz.

Complex Permeability

As is consistent with electrical engineering principles in which alternating voltages and currents are denoted by complex parameters, so the permeability of a material can be represented as a complex parameter consisting of a real and an imaginary part. This is evidenced at high frequencies where the permeability separates into two components. The real



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component (μ') represents the reactive portion, and is in phase with the alternating magnetic field, whereas the imaginary component (μ'') represents the losses, and is out of phase with the alternating magnetic field.

These may be expressed as series components (μ'_s, μ''_s) or parallel components (μ'_p, μ''_p). The graphs in Figures 1, 2 and 3 show the series components of the complex initial permeability as a function of frequency for three ferrite

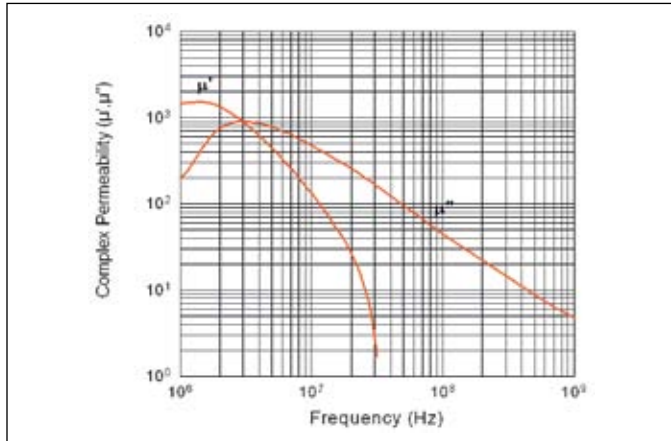


Figure 1

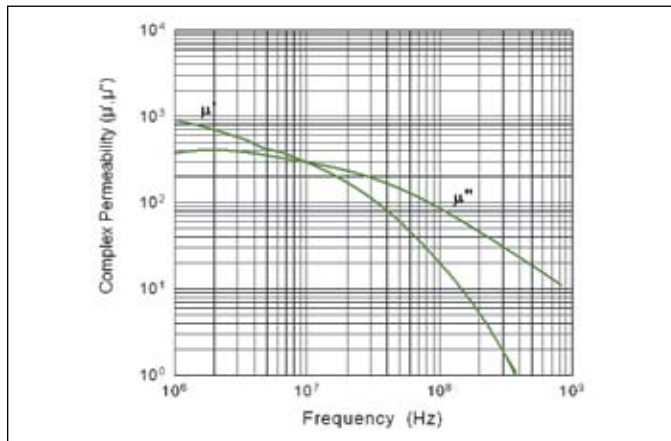


Figure 2

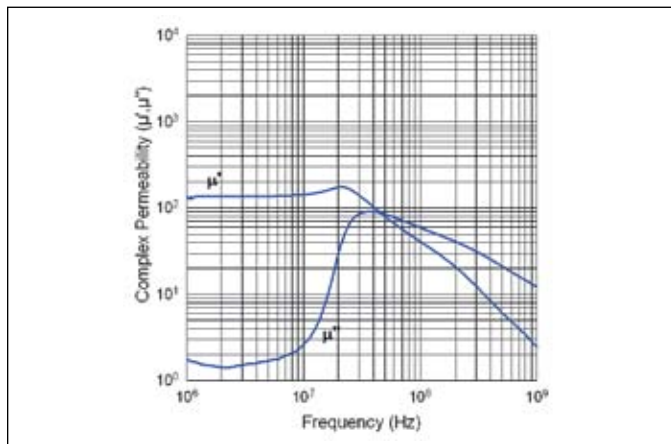


Figure 3

materials. Material type 73 is a manganese zinc ferrite with an initial permeability of 2500. Material type 43 is a nickel zinc ferrite with an initial permeability of 850. Material type 61 is a nickel-zinc ferrite with an initial permeability of 125.

Concentrating on Figure 3, the series components of 61 type material, we see that the real part of the permeability, μ'_s , remains constant with increasing frequency until a critical frequency is reached and then decreases rapidly. The losses, or μ''_s , rise, then peak as μ'_s falls. This decrease in μ'_s is due to the onset of ferrimagnetic resonance². It should be noted that the higher the permeability, the lower the frequency at which this occurs. This inverse relationship was first observed by Snoek and given the following formula:

$$f_{\text{res}} = \frac{\gamma M_{\text{sat}}}{3\pi(\mu_i - 1)} \text{ Hz} \quad \text{Equation 1}$$

Where:

f_{res} = frequency at which μ''_s is maximum
 γ = gyromagnetic ratio = $0.22 \times 10^6 \text{ A}^{-1} \text{ m}$
 μ_i = initial permeability
 M_{sat} = 250-350 Am^{-1}

This same Equation can be approximated by:

$$f_{\text{res}} = B_{\text{sat}}/\mu_i \text{ MHz} \quad \text{Equation 2}$$

Since ferrite cores used in low signal level and power applications are concerned with magnetic parameters below this frequency, rarely does the ferrite manufacturer publish data for permeability and/or losses at higher frequencies. However, higher frequency data is essential when specifying ferrite cores used in the suppression of EMI.

Relationship Between Complex Permeability and Impedance

The characteristic that is specified by most ferrite manufacturers for components used in EMI suppression is impedance. Impedance is easily measured on readily available commercial analyzers with direct digital readouts. Unfortunately, impedance is usually specified at particular frequencies and is the scalar quantity representing the magnitude of the complex impedance vector. Although this information is valuable, it is often not sufficient, especially when modeling the ferrite's circuit performance. In order to accomplish this, the impedance value and phase angle for the components, or the complex permeability for the specific material, must be available.

But even before beginning to model the performance of a ferrite component in a circuit, the designer should know the following:

- The frequency of unwanted signals;
- The source of the EMI (radiated/conducted);

- Operating conditions (environment);
- If high resistivity is required because of multiple turns, conductor pins in a connector filter plate or position in the circuit;
- The circuit impedance, source and load;
- How much attenuation is required;
- The allowable space on the board.

The design engineer can then compare materials at the relevant frequencies for the complex permeability, heeding effects of temperature and field strength. After this, core geometry can be selected, from which the inductive reactance and series resistance can be defined.

The Equations

The impedance of a ferrite core in terms of permeability is given by:

$$Z = j\omega\mu L_o \quad \text{Equation 3}$$

And:

$$\mu = \mu' - j\mu'' = (\mu_s'^2 + (j\mu_s'')^2)^{1/2} \quad \text{Equation 4}$$

Where:

μ' = real part of the complex permeability

μ'' = imaginary part of the complex permeability

j = unit imaginary vector

L_o = the air core inductance

Therefore:

$$Z = j\omega L_o (\mu' - j\mu'') \quad \text{Equation 5}$$

The impedance of the core is also considered to be a series combination of inductive reactance (X_L) and the loss resistance (R_s), both of which are frequency dependent. A loss free core would have an impedance that would be given by the reactance:

$$X = j\omega L_s \quad \text{Equation 6}$$

A core that has magnetic losses may be represented as having an impedance:

$$Z = R_s + j\omega L_s \quad \text{Equation 7}$$

Where:

R_s = total series resistance = $R_m + R_c$

R_m = Equivalent series resistance due to the magnetic losses

R_c = equivalent series resistance for copper losses

At low frequencies, the impedance of the component is primarily the inductive reactance. As frequency increases, the inductance decreases at the same time the losses increase and the total impedance increases. Figure 4 is a typical curve of X_L , R_s and Z vs. frequency for our a medium permeability material.

Knowing that, the magnetic quality factor:

$$Q = \mu'/\mu'' = \omega L_s/R_s \quad \text{Equation 8}$$

Then, the inductive reactance is made directly proportional to the real part of the complex permeability by L_o , the air core inductance:

$$j\omega L_s = j\omega L_o\mu'$$

The loss resistance is also made directly proportional to the imaginary part of the complex permeability by the same constant:

$$R_s = \omega L_o\mu''$$

Substituting into Equation 7 for impedance:

$$Z = \omega L_o\mu'' + j\omega L_o\mu'$$

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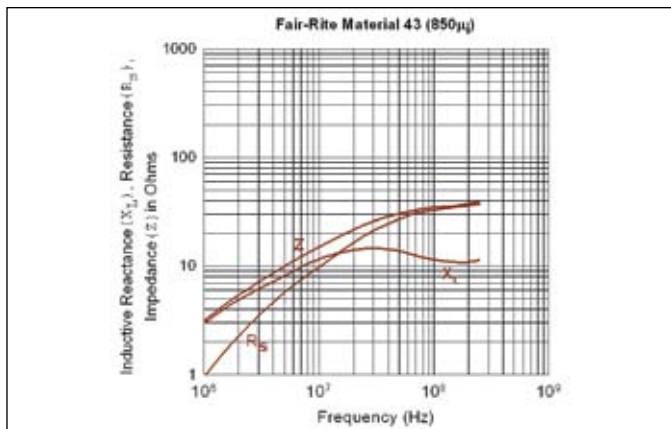


Figure 4

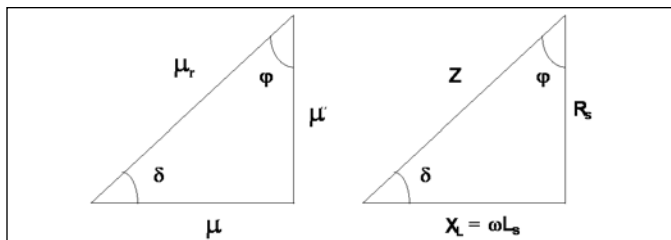


Figure 5

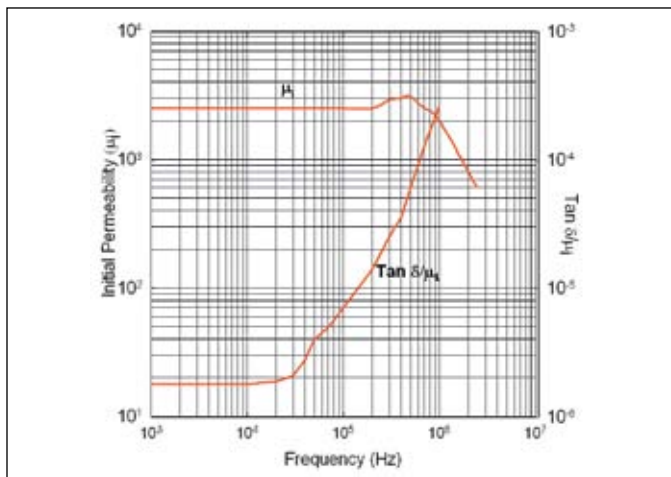


Figure 6

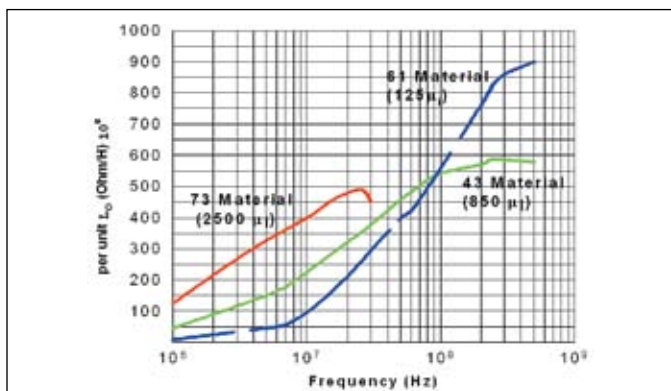


Figure 7

And factoring:

$$Z = j \omega L_o (\mu'_s - j \mu''_s) \quad \text{Equation 9}$$

In Equation 9, the core material is given by μ'_s and μ''_s , and the core geometry is given by L_o . Thus, knowing the complex permeability for different ferrites, a comparison can be made to obtain the most suitable material at the desired frequency or frequency range. After the optimum material is chosen, the best size component can be selected. The vector representation for both the complex permeability and impedance is found in Figure 5.

If the manufacturer supplies graphs of complex permeability vs frequency for the ferrite materials recommended for suppression applications, then a comparison of cores shapes and core materials for optimizing impedance is straight forward. Unfortunately, this information is rarely made available. However, most manufacturers supply curves of initial permeability and losses vs. frequency. From this data, a comparison of materials for optimizing core impedance can be obtained.

Material Selection--Example

Referring to Figure 6 (Initial Permeability & Loss Factor³ vs. Frequency for Fair-Rite 73 material), suppose a designer wants to guarantee maximum impedance between 100 and 900 kHz. 73 material is chosen. For purposes of modeling, the designer also needs to know the reactive and resistive portions of the impedance vector at 100 kHz (105 Hz) and 900 kHz. This information can be derived from the graphs as follows:

$$\text{At } 100\text{kHz}, \mu'_s = \mu_i = 2500$$

And:

$$(\text{Tan } \delta / \mu_i) = 7 \times 10^{-6}$$

Since:

$$\text{Tan } \delta = \mu''_s / \mu'_s$$

Then:

$$\mu''_s = (\text{Tan } \delta / \mu_i) \times (\mu_i)^2 = 43.8$$

Calculating for the complex permeability:

$$\mu = \mu' - j\mu'' = ((\mu_s'^2 + (j\mu_s'')^2)^{1/2} = 2500.38$$

It should be noted that, as expected, μ'' adds very little to the total permeability vector at this low frequency. The impedance of the core is primarily inductive.

However at 900 kHz, μ''_s has become a significant contributor:

$$\mu'_s = 2100, \mu''_s = 1014 \mu = 2332$$

Core Selection

The designer knows that the core must accept a #22 wire, and fit into a space of 10 mm by 5 mm. The inside diameter will be specified as .8 mm. Solving for the estimated impedance and its components, first a bead with an outside diameter of 10 mm and a height of 5 mm is chosen:

at 100 kHz

Since:

$$Z = \omega L_o \mu \text{ and Toroidal } L_o = .0461 N^2 \log^{10} (OD/ID) Ht 10^{-8} \text{ (H)}$$

Then:

$$Z = \omega L_o (2500.38) = (6.28 \times 10^5) \times .0461 \times \log^{10} (10/.8) \times 5 \times (2500.38) \times 10^{-8} = 3.97 \text{ ohms}$$

Where:

$$R_s = L_o \omega \mu_s'' = .069 \text{ ohms}$$

$$X_L = L_o \omega \mu_s' = 3.97 \text{ ohms}$$

at 900 kHz

$$Z = 33.3 \text{ ohms, } R_s = 14.48 \text{ ohms, } X_L = 30.0 \text{ ohms}$$

Then a bead with an outside diameter of 5 mm and a length of 10 mm is selected:

at 100 kHz

$$Z = \omega L_o (2500.38) = (6.28 \times 10^5) \times .0461 \times \log^{10} (5/.8) \times 10 \times (2500.38) \times 10^{-8} = 5.76 \text{ ohms}$$

Where:

$$R_s = L_o \omega \mu_s'' = .100 \text{ ohms}$$

$$X_L = L_o \omega \mu_s' = 5.76 \text{ ohms}$$

at 900 kHz

$$Z = 48.1 \text{ ohms, } R_s = 20.9 \text{ ohms, } X_L = 43.3 \text{ ohms}$$

In this instance, as in most, maximum impedance is achieved by using a smaller OD with the longer length. If the ID were larger (for instance 4 mm), the reverse should have been true.

This same approach can be used if graphs of Impedance per unit Lo and phase angle vs. frequency are supplied. Figures 9, 10 and 11 are representative of such curves for the same three materials used throughout this article.

Example

The designer wants to guarantee maximum impedance for the frequency range of 25 MHz to 100 MHz. The available board space is again 10 mm by 5 mm and the core must accept a

#22 awg wire. Referring to Figure 7, Impedance per unit Lo for three ferrite materials, or Figure 8, complex permeability for the same three materials, an 850 μi material is chosen⁴. Using the graph of Figure 9, Z/Lo for the medium permeability material, at 25 MHz, is 350 × 10⁸ ohm/H.

Solving for the estimated impedance:

$$Z = 350 \times 10^8 \times .0461 \times \log^{10} (5/.8) \times 10 \times 10^{-8}$$

$$Z = 128.4 \text{ ohm } \Phi = 30 \text{ degrees}$$

$$X_L = Z \sin \Phi = 126.8 \text{ ohms}$$

$$R_s = Z \cos \Phi = 19.81 \text{ ohms}$$

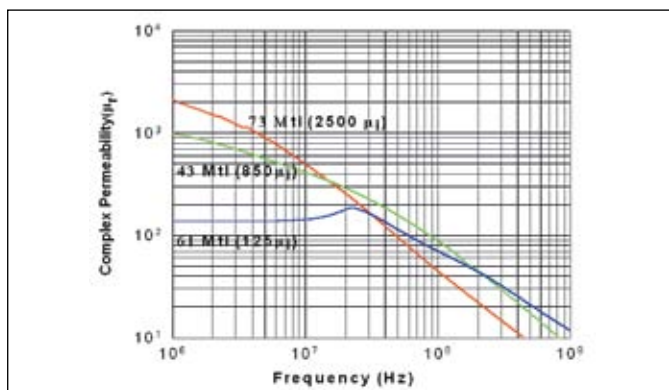


Figure 8

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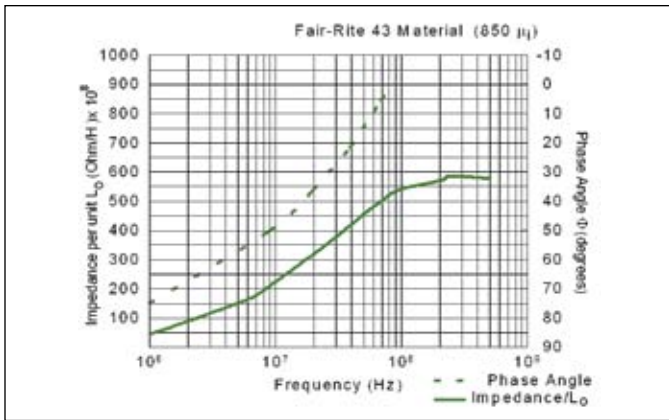


Figure 9

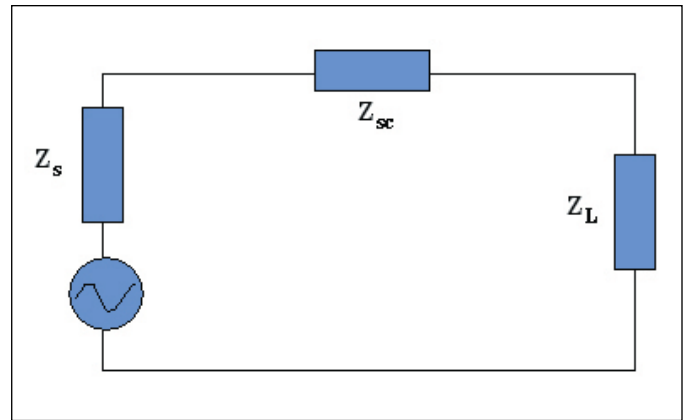


Figure 13

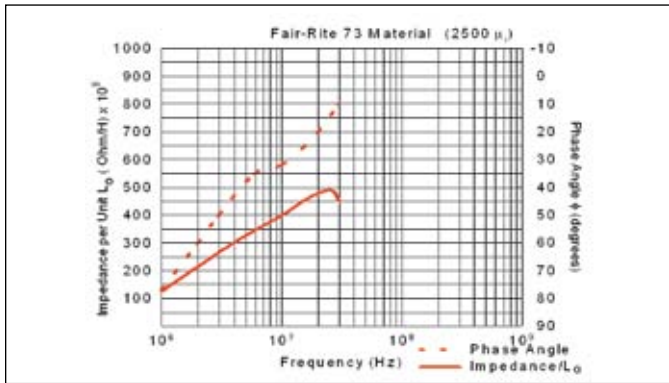


Figure 10

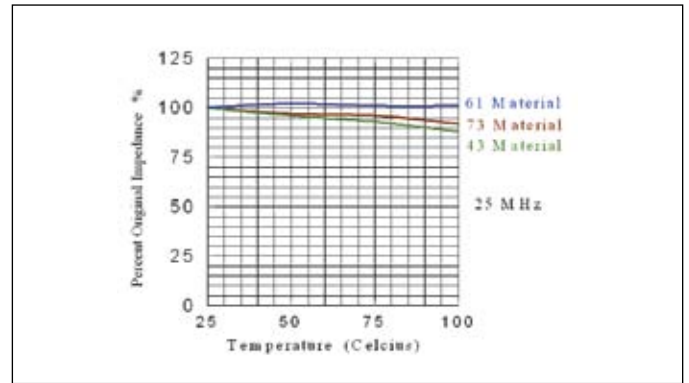


Figure 14

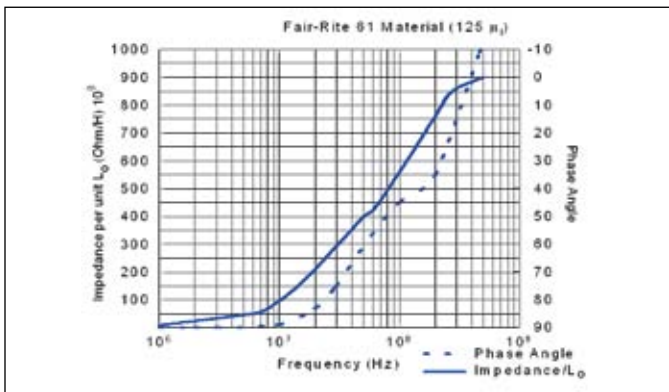


Figure 11

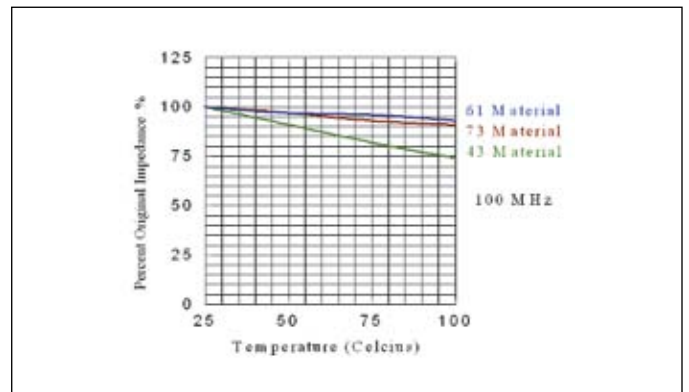


Figure 15

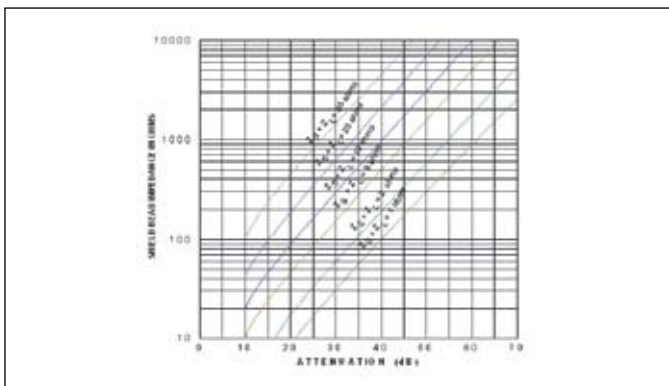


Figure 12

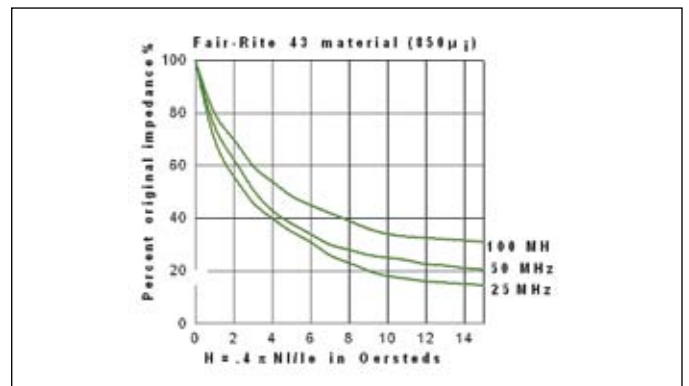


Figure 16

And, at 100 MHz

$$Z = 179.8 \text{ ohms } \Phi = 0$$
$$X_L = 0 \text{ ohms } R_s = 179.8 \text{ ohms}$$

The same approach may be used for different materials, dimensions, and frequencies.

The previous discussion assumed that the core of choice was cylindrical. If the ferrite core being used is for flat ribbon, or bundled cable, or a multi-hole plate, the calculation for the L_o becomes more difficult, and fairly accurate figures for the cores path length and effective area must be obtained in order to calculate the air core inductance. This can be done by mathematically sectioning the core and summing the calculated path length and magnetic area for each section. In all cases though, an increase or decrease in impedance will be directly proportional to an increase or decrease in the height/length of the ferrite core.⁵

Relationship Between Impedance and Attenuation

As stated, most manufacturers are specifying cores for EMI applications in terms of impedance, but often the end user needs to know the attenuation. The relationship that exists between these two parameters is:

$$\text{Attenuation} = 20 \log^{10} ((Z_s + Z_{sc} + Z_L) / (Z_s + Z_L)) \text{ dB}$$

Where:

$$Z_s = \text{Source impedance}$$
$$Z_{sc} = \text{Suppressor core impedance}$$
$$Z_L = \text{Load impedance}$$

The relationship is dependent on the impedance of the source generating the noise and the impedance of the load receiving it. These values are usually complex numbers that can be infinite in scope and not easily obtained by the designer. Selecting a value of one ohm for both the load and the source impedance (as may be the case when the source is a switch mode power supply and the load many low impedance circuits) simplifies the equation and allows comparison of ferrite cores in terms of attenuation.

Under these conditions, the equation reduces to:

$$\text{Attenuation} = 20 \log^{10} (Z_{sc}/2) \text{ dB}$$

The graph in Figure 12 is a family of curves that show the relationship between the shield bead impedance and the attenuation for a number of commonly used values of the load plus the generator impedance.

Figure 13 is the equivalent circuit of an interference source with an internal impedance of Z_s , generating an interference signal through the series impedance of the suppressor core Z_{sc} and the load impedance Z_L .

The Environment


Temperature

As stated, ferrite's magnetic parameters can be affected by temperature and field strengths.

Figures 14 and 15 are graphs of impedance vs. temperature for the same three ferrite materials. The most stable of these materials is the 61 material, with a decrease in impedance of 8% at 100° C and 100 MHz. This is compared to a 25% drop in impedance for the 43 material at the same frequency and temperature. These curves, when supplied, may be used to adjust the specified room temperature impedance if desired attenuation is to be at elevated temperatures.

Field Strength

As in the case of temperature, dc and 50 or 60 Hz power current will also affect the same intrinsic ferrite characteristics which, in turn, will result in lowering of the impedance of the core. Figures 16, 17 and 18 are typical of curves that illustrate the effect of biases on impedance a ferrite material. The curve depicts the degradation of impedance as a function of field




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Definitions/Equations

Air Core Inductance - L_0 (H)

The inductance that would be measured if the core had unity permeability and the flux distribution remained unaltered.

General formula $L_0 = 4\pi N^2 10^{-9} (H) C^1$

Toroidal $L_0 = .0461 N^2 \log^{10} (OD/ID) Ht 10^{-8} (H)$

Dimensions in mm's

Attenuation - A (dB)

The decrease in signal magnitude in transmission from one point to another. It is a scalar ratio of the input magnitude to the output magnitude in decibels.

Core Constant - C^1 (cm^{-1})

The summation of the magnetic path lengths of each section of a magnetic circuit divided by the corresponding magnetic area of the same section.

Core Constant - C^2 (cm^{-3})

The summation of the magnetic path lengths of each section of a magnetic circuit divided by the square of the corresponding magnetic area of the same section.

Effective Dimensions of a Magnetic Circuit

Area A_e (cm^2), Path Length l_e (cm) and Volume V_e (cm^3)

For a magnetic core of given geometry, the magnetic path length, the cross-sectional area and the volume that a hypothetical toroidal core of the same material properties should possess to be the magnetic equivalent to the given core.

Field Strength - H (oersted)

The parameter characterizing the amplitude of the field strength.

$H = .4 \pi NI/l_e$ (oersted)

Flux Density - B (gauss)

The corresponding parameter for the induced magnetic field in a area perpendicular to the flux path.

Impedance - Z (ohm)

The impedance of a ferrite may be expressed in terms of its complex permeability.

$Z = j \omega L_s + R_s = j \omega L_0 (\mu'_s - j \mu''_s)$ (ohm)

Loss Tangent - $\tan \delta$

The loss tangent of the ferrite is equal to the reciprocal of the Q of the circuit.

Loss Factor - $\tan \delta/\mu_i$

The phase displacement between the fundamental components of the flux density and the field strength divided by the initial permeability.

Phase Angle - Φ

The phase shift between the applied voltage and current in a inductive device.

Permeability - μ

The permeability obtained from the ratio of the flux density and the applied alternating field strength is:

Amplitude Permeability, μ_a - when stated values of flux density, are greater than that used for initial permeability.

Effective Permeability, μ_e - when a magnetic circuit is constructed with an airgap or airgaps, and then the permeability is that of a hypothetical homogeneous material which would provide the same reluctance.

Incremental Permeability, $\mu\Delta$ - when a static field is superimposed.

Initial Permeability, μ_i - when the flux density is kept below 10 gauss.

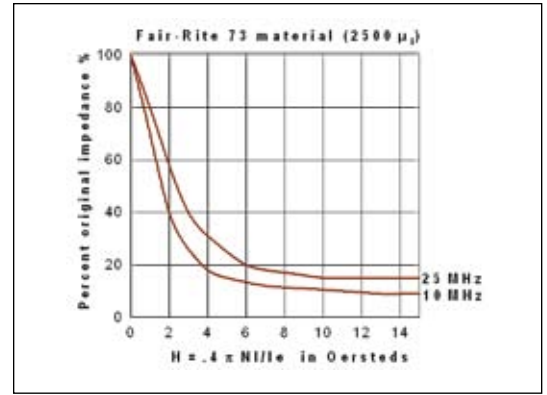


Figure 17

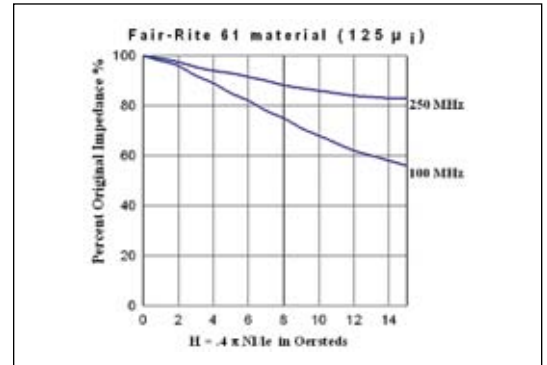


Figure 18

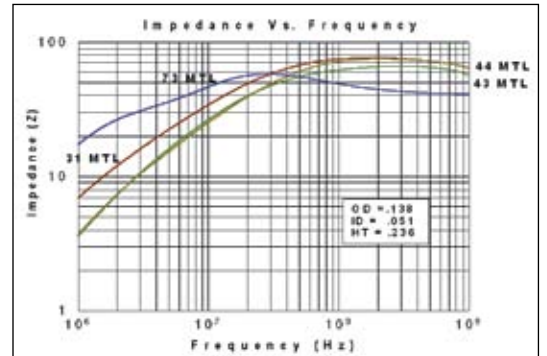


Figure 19

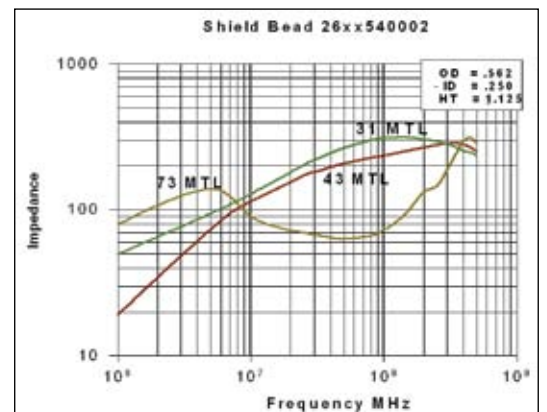


Figure 20

strength for a specific material as a function of frequency. It should be noted that, as frequency increases, the effect of biases diminishes.

New Materials

Since the compilation of this data, our company has introduced two new materials. Our 44 is a nickel zinc, medium permeability material, while 31 is a manganese zinc high permeability material.

Figure 19 is a plot of impedance vs. frequency for the same size bead in 31, 73, 44 and 43 materials. 44 material is an improved 43 material with higher dc resistivity, 10^9 ohm cm, better thermal shock characteristics, temperature stability and higher curie temperature (T_c). When compared to our 43 material, 44 material has slightly higher impedance vs. frequency characteristics.

Still, material 31 exhibits higher impedance than either 43 or 44 throughout the measured frequency range. Designed to alleviate the problem of dimensional resonance that affects low frequency suppression performance of the larger manganese-zinc cores, 31 has found successful applications as cable connector suppressor cores and large toroidal cores. Figure 20 is a curve of impedance vs frequency for 43, 31, and 73 material for a Fair-Rite core with an OD of .562", ID of .250 and a HT of 1.125.

When comparing Figure 19 to Figure 20, it should be noted that for the smaller core in Figure 19, for frequencies up to 25 Mhz, 73 material is the optimum suppression material. However, as the core cross section increases, the maximum frequency decreases, as can be shown by the data in Figure 20, where the highest frequency where 73 is optimum is 8 Mhz.

Also noteworthy is that 31 material is superior from 8 MHz to 300 MHz. However, being a manganese zinc ferrite, 31 material has a much lower volume resistivity of 102 ohm-cm and exhibits greater changes in impedance with extreme temperature variation. □

Carole U. Parker is the president of Fair-Rite Products Corporation, and can be reached at parker@fair-rite.com.

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Notes

1. In phase is when the maxima and minima of the magnetic field, H, and those of the induction B, coincide. Out of phase is when the maxima and minimum is displaced by 90°.
2. Ferromagnetic Resonance is also called spin precession resonance.
3. It should be noted that the impedance for each ferrite material is optimum over a specific frequency range. As a rule of thumb, the higher the permeability, the lower the frequency range.
4. It should be noted that the impedance for each ferrite material is optimum over a specific frequency range. As a rule of thumb, the higher the permeability, the lower the frequency range.
5. This remains true so long as the increase in height/length does not cause the core to be in dimensional resonance.

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