Specifying a Ferrite for EMI Suppression

CAROLE U. PARKER
Fair-Rite Products Corp., Wallkill, NY

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.

Introduction

This article is written as a revision to "Choosing a Ferrite for the Suppression of EMI."[1] Whereas the focus of the previous article was on the impedance of the core, this discussion will include an examination of the intrinsic characteristic of the ferrite material, the complex permeability. It will relate this to the ferrite component's impedance, while analyzing the effects of frequency, field strength, temperature and core geometry. It is meant to aid designers when modeling ferrite cores in their circuits.

Ferrite Applications

The following are three major applications for soft ferrite:

- Low signal level
- Power
- EMI

Each specific application dictates the required intrinsic material characteristics and required core geometry. For low signal level applications the intrinsic characteristics required of the ferrite are controlled 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 switch mode 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 lowpass filter that is inductance-capacitance at low frequencies and dissipative at higher frequencies.

The third, and most common use, is when the 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 the EMI frequencies, and zero impedance at all other frequencies. In reality, ferrite suppresser cores provide a frequency-dependent impedance, which is low at frequencies below 1 MHz. Depending upon the ferrite material, the maximum impedance 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 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. (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 minima is displaced by 90°.)

The real and imaginary components 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 materials, a manganese-zinc ferrite with an initial permeability of 2500, a nickel-zinc ferrite with an initial permeability of 850, and a nickel-zinc ferrite with an initial permeability of 125.

Concentrating on Figure 3, the series components of the nickel-zinc ferrite with an initial permeability of 125, 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 ferromagnetic resonance, also called spin precession resonance. 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 is given in the following formula:

$$f_{res} = \frac{\gamma \text{ Msat (Hz)}}{3\pi (\mu_i - 1)} \qquad (1)$$

where

f_{res} = Frequency at which μ_s'' is maximum

γ = Gyromagnetic ratio

Key Terms

Air Core Inductance – L_o (H)
The inductance that would be measured if the core had unity permeability and the flux distribution remained unaltered.
General formula $L_o = \frac{4\pi N^2 10^{-9}}{C_1}$ (H)
Toroidal $L_o = 0.0461\ N^2 \log_{10}$ (OD/ID) Ht 10^{-8} (H)
Dimensions in mm

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.
$H = 0.4\ \pi\ NI/l_e$ (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.
$Z = j\omega L_s + R_s = j\omega Lo(\mu_s' - j\mu_s'')$ (ohm)

Loss Tangent – tan δ
The loss tangent of the ferrite is equal to the reciprocal of the Q of the circuit.

Loss Factor – tan δ/μ_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 an inductive device.

Permeability – μ
The permeability obtained from the ratio of the flux density and the applied alternating field strength.

- 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 air gap or air gaps, and then the permeability is that of a hypothetical homogeneous material which would provide the same reluctance.
- Incremental Permeability μ_Δ – when a static field is superimposed.
- Initial Permeability μ_i – when the flux density is kept below 10 gauss.

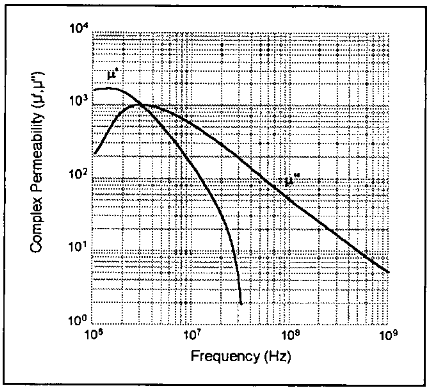

***Figure 1**. Manganese-zinc Ferrite with Initial Permeability of 2500.*

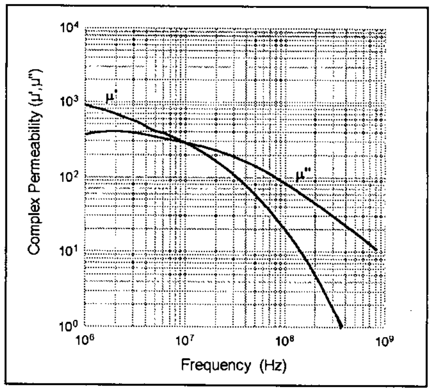

***Figure 2**. Nickel-zinc Ferrite with Initial Permeability of 850.*

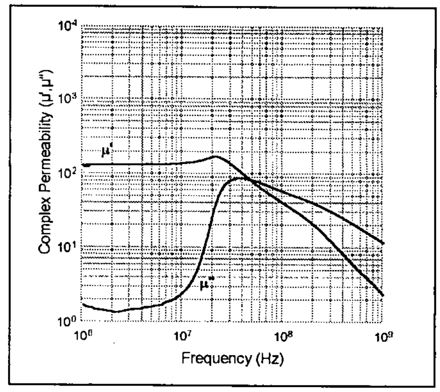

***Figure 3**. Nickel-zinc ferrite with Initial Permeability of 125.*

$= 0.22 \times 10^6\ A^{-1}\ m$

μ_i = Initial permeability

M_{sat} = 250-350 Am^{-1}

This same equation can be approximated by:

$$f_{res} = B_{sat} / \mu_i \text{ (MHz)} \qquad (2)$$

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 the impedance. The impedance is easily measured on readily available commercial analyzers with direct digital readouts. Unfortunately, the 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:

- Frequency of unwanted signals
- 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
- Circuit impedance, source and load
- How much attenuation is required
- Allowable space on the board

The design engineer can then compare materials at the relevant frequencies for the complex permeability, heeding the 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:

$$Z = j\omega\mu L_o \qquad (3)$$

and

$$\mu = \mu' - j\mu'' = (\mu_s'^2 + (j\mu''_s)^2)^{1/2} \qquad (4)$$

where

μ' = Real part of the complex permeability

μ'' = Imaginary part of the complex permeability

j = Unit imaginary vector

L_o = Air core inductance

Therefore,

$$Z = j\omega L_o (\mu' - j\mu'') \qquad (5)$$

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:

$$X = j\omega L_s \qquad (6)$$

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

$$Z = R_s + j\omega L_s \qquad (7)$$

where

R_s = Total series resistance = $R_m + R_e$

R_m = Equivalent series resistance due to the magnetic losses

R_e = Equivalent series resistance for copper losses

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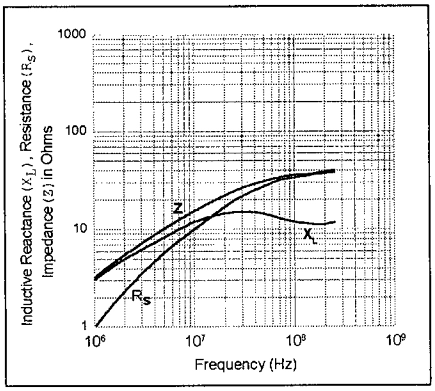

Figure 4. *Inductive Reactance, Impedance and Resistance of a Medium Permeability Material.*

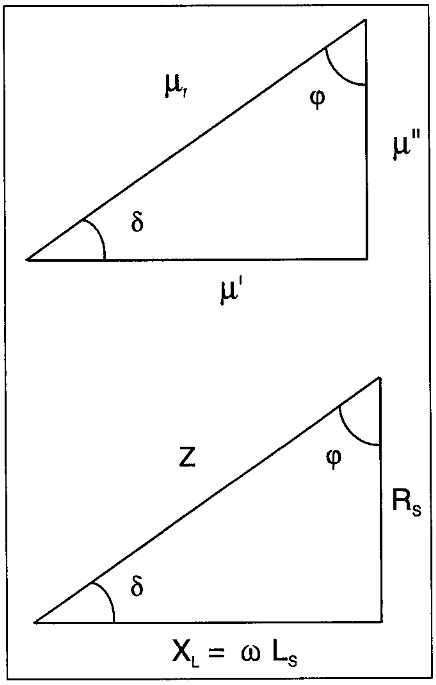

Figure 5. *Vector Representations for Complex Permeability and Impedance.*

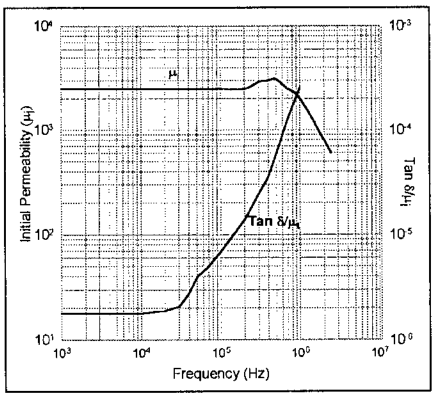

Figure 6. *Initial Permeability and Loss Factor vs. Frequency for the Manganese-zinc Ferrite with an Initial Permeability of 2500.*

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 versus frequency for a medium permeability material.

Knowing that the magnetic quality factor

$$Q = \mu'/\mu'' = \omega L_S/R_S \qquad (8)$$

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

$$j\omega L_S = j\omega L_O \mu_S'$$

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

$$R_S = \omega L_O \mu_S''$$

Substituting into Equation (7) for impedance:

$$Z = \omega L_O \mu_S'' + j\omega L_O \mu_S'$$

and factoring:

$$Z = j\,\omega\,L_O\,(\mu_S' - j\mu_S'') \qquad (9)$$

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 versus frequency for the ferrite materials recommended for suppression applications, then a comparison of core shapes and core materials for optimizing impedance is straightforward. Unfortunately this information is rarely made available. However, most manufacturers supply curves of initial permeability and losses versus frequency. From this data a comparison of materials for optimizing core impedance can be obtained.

Material Selection

EXAMPLE: 100 kHz – 900 kHz

Referring to Figure 6, which describes the initial permeability and loss factor versus frequency for the manganese-zinc ferrite with an initial permeability of 2500, assume a designer wants to guarantee maximum impedance between 100 and 900 kHz. (The loss factor, the normalization of loss tangent per unit of permeability, is a material property describing the loss characteristics per unit of permeability.) The material described above is chosen. For purposes of modeling, the designer also needs to know the reactive and resistive portions of the impedance vector at 100 kHz (10^5 Hz) and 900 kHz. This information can be derived from the graphs as follows:

At 100 kHz

$$\mu_S' = \mu_i = 2500 \text{ and}$$
$$(\text{Tan}\ \delta/\mu_i) = 7 \times 10^{-6}$$

Since

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

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 (ID) will be specified as .8 mm. Solving for the estimated impedance and its components, a bead with an outside diameter (OD) of 10 mm and a height of 5 mm is chosen first:

At 100 kHz
since

$$Z = \omega L_o \mu$$

and

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

then

$Z = \omega L_o (2500.38)$
$= (6.28 \times 10^5) \times .0461 \times \log_{10}(10/.8) \times 5 \times 2500.38) \times 0^{-8}$
$= 3.97$ ohms

where

$R_s = L_o\ \omega\ \mu_s'' = .069$ ohms
$X_L = L_o\ \omega\ \mu_s' = 3.97$ ohms

At 900 kHz

$Z = 33.3$ ohms, $R_s = 14.48$ ohms, $X_L = 30.0$ ohms

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

At 100 kHz

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

where

$R_s = L_o\ \omega\mu_s'' = .100$ ohms
$X_L = L_o\ \omega\mu_s' = 5.76$ ohms

At 900 kHz

$Z = 48.1$ ohms, $R_s = 20.9$ ohms, $X_L = 43.3$ 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 would have been true.

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

Example: 25 MHz - 100 MHz

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, which describes impedance per unit L_o for three ferrite materials, or Figure 8, complex permeability for the same three materials, an 850 μ_i material is chosen. (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.) Using the graph of Figure 9, Z/L_o for the medium permeability material, at 25 MHz, is 350×10^8 ohm/H. Solving for the estimated impedance:

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

$Z = 128.4$ ohm $\Phi = 30$ degrees

$X_L = Z \sin \Phi = 126.8$ ohms
$R_s = Z \cos \Phi = 19.81$ ohms

At 100 MHz

$Z = 179.8$ ohms $\Phi = 0$
$X_L = 0$ ohms $Rs = 179.8$ 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 core 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 divided path length by the 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. (This remains true so long as the increase in height/length does not cause the core to be in dimensional resonance.)

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 = Source impedance
Z_{sc} = Suppressor core impedance
Z_L = 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 1 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 versus temperature for the same three ferrite materials. The most stable of these materials is the nickel-zinc, 125 initial permeability 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, can 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 the impedance of the core. Figures 16, 17 and 18 are typical of curves that illustrate the effect of biases on impedance of a ferrite material. The curve depicts the degradation of impedance as a function of field 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, two new materials have been developed, a nickel-zinc, medium-permeability material and a manganese-zinc high-permeability material.

Figure 19 is a plot of impedance vs. frequency for the same size bead in four different materials. The new nickel zinc material is an improved version of an existing ferrite with higher dc resistivity, 10^9 ohm-cm, better thermal shock characteristics, temperature stability and higher Curie temperature (T_c). When compared to its predecessor, the new material has slightly higher impedance vs. frequency characteristics. Still, the new manganese-zinc material exhibits higher impedance than either of the nickel-zinc materials throughout the measured frequency range. Designed to alleviate the problem of dimensional resonance that affects the low frequency suppression performance of the larger manganese-zinc cores, the

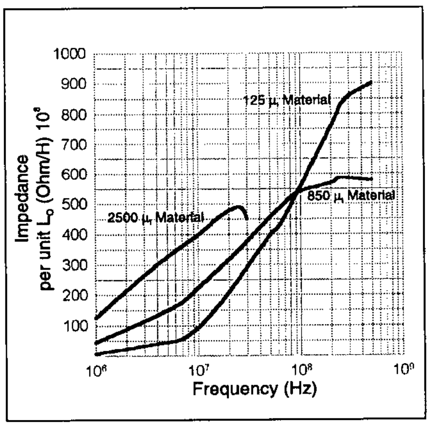

Figure 7. *Impedance Per Unit.*

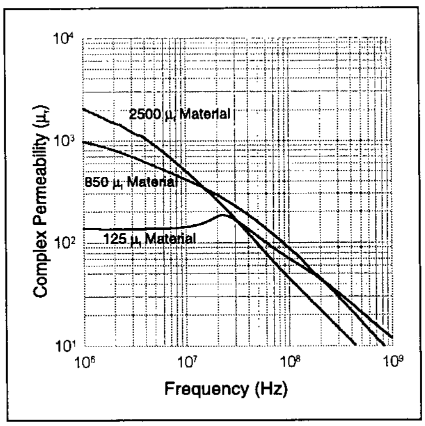

Figure 8. *Complex Permeability.*

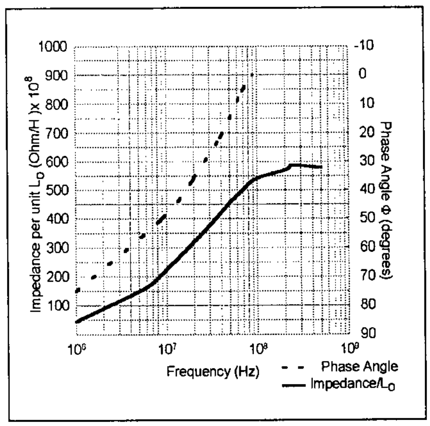

Figure 9. *Impedance per Unit L_o for 850 Initial Permeability Material.*

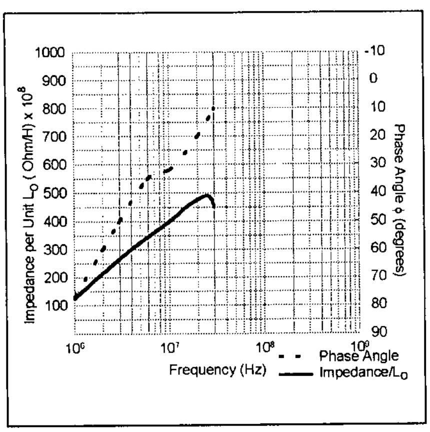

Figure 10. *Impedance per Unit L_o for 2500 Initial Permeability Material.*

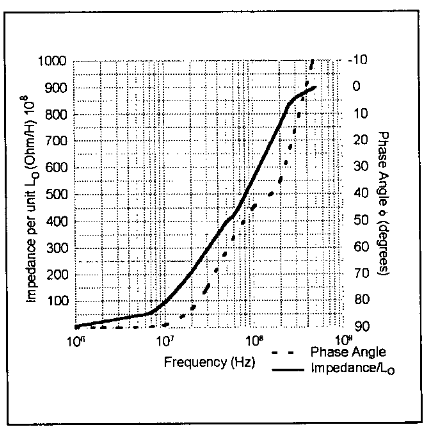

Figure 11. *Impedance per Unit L_o for 125 Initial Permeability Material.*

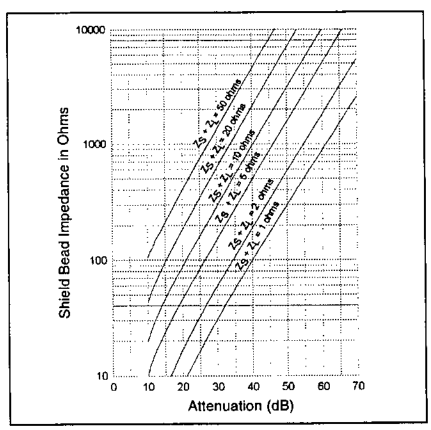

Figure 12. *Relationship between the Shield Bead Impedance and the Attenuation.*

manganese-zinc material has found successful applications as cable connector suppressor cores and large toroidal cores.

Figure 20 is a curve of impedance versus frequency for several materials for a core with the following geometry: an OD of 0.562", ID of 0.250 and a height 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, the manganese-zinc ferrite with an initial permeability of 2500 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, the highest frequency where it is optimum is 8 MHz. Also noteworthy is that the manganese-zinc high perme-

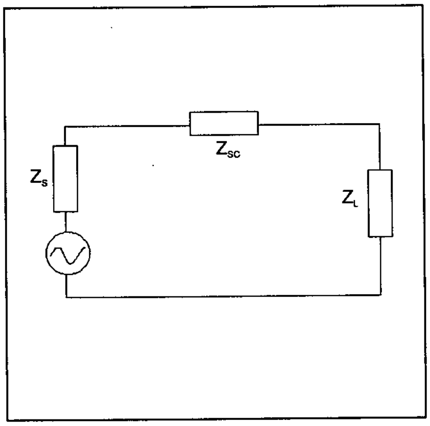

Figure 13. Interference Source.

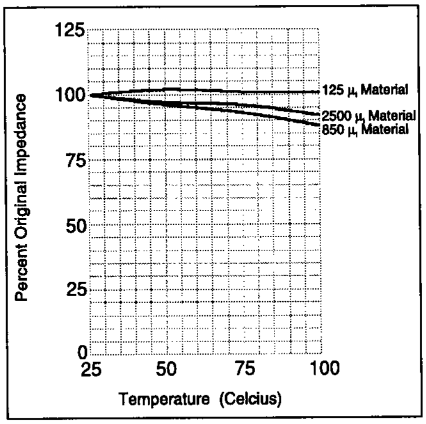

Figure 14. Impedance vs. Temperature at 25 MHz.

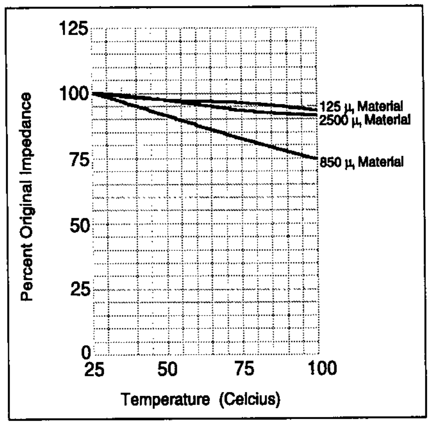

Figure 15. Impedance vs. Temperature at 100 MHz.

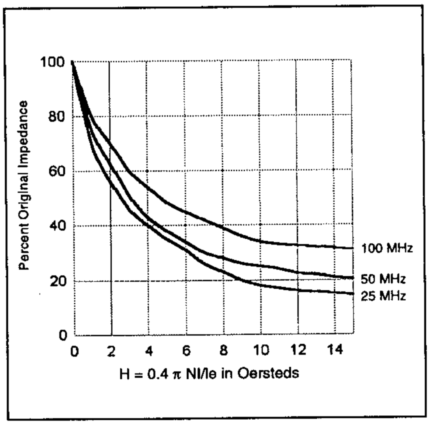

Figure 16. Effect of Biases on Impedance for 850 μ_i Material.

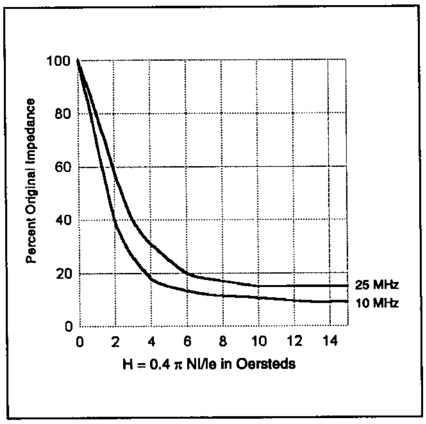

Figure 17. Effect of Biases on Impedance for 2500 μ_i Material.

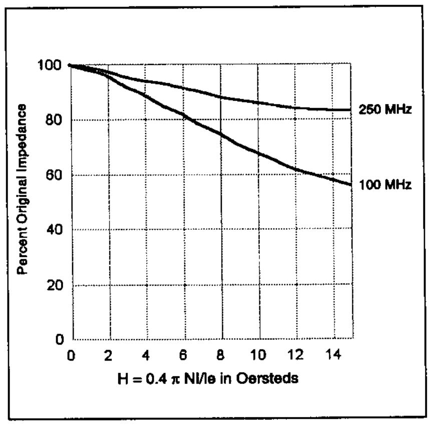

Figure 18. Effect of Biases on Impedance for 125 μ_i Material.

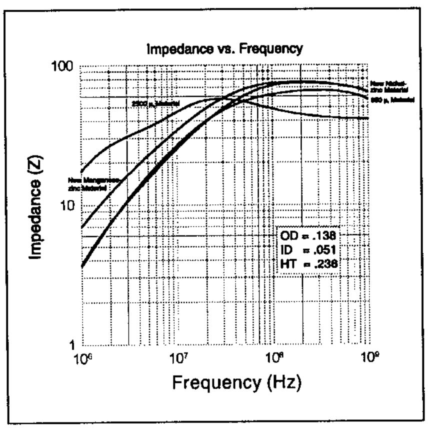

Figure 19. Impedance Versus Frequency for New Manganese-zinc Material.

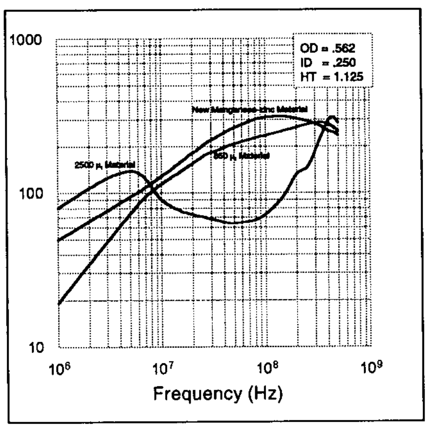

Figure 20. Comparison of Core Impedance Manufactured from Different Ferrite Materials.

ability material is superior from 8 MHz to 300 MHz. However, being a manganese-zinc ferrite, it has a much lower volume resisitivity of 10^2 ohm-cm and exhibits greater changes in impedance with extreme temperature variation.

Conclusion

Ferrites used for the suppression of electromagnetic interference can be thought of as high-frequency dependent resistors. Selecting the optimum ferrite material for a specific frequency or frequency range is simplified if the intrinsic characteristic, complex permeability, is supplied by the manufacturer. However, as a minimum, both impedance and phase angle for specific cores in specific materials, under stated environmental conditions, should be made available to the designer.

Ferrite cores are manufactured in numerous materials and geometries, for a broad frequency range. They are easy to use and remain an inexpensive solution to what can often be a very costly problem.

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1. Carol U. Parker, "Choosing a Ferrite for the Suppression of EMI," *ITEM 93,* p.112.

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***CAROLE PARKER** has a Bachelor's Degree in electrical engineering and a Master's Degree in business administration from Rensselaer Polytechnic Institute. She has been employed by Fair-Rite Products Corporation for over twenty years. She started as an application engineer in 1974, was promoted to director of marketing and sales in 1993, and became President of the company in 1996. (914) 895-2055.*