Chapter

# Characterization of Nanocrystalline Cores for EMI Suppression in Cables

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## Abstract

Electromagnetic interferences (EMI) can cause different kinds of problems in digital and analog systems, leading to malfunctions, system reboots, or even permanent damage to the system if this is not adequately designed or protected. Nowadays, most electronic products are connected to the main power network or are designed to be interconnected with others through cables. These cable interconnections are becoming more difficult due to the rigid restrictions related to the accomplishment of electromagnetic compatibility (EMC) compliance. When the cables of a system represent an EMI source, it cannot pass the conducted or radiated emissions test. A widely used technique to reduce these problems is applying an EMI suppressor such as a sleeve core. This EMI suppressor provides selective attenuation of undesired interference components that the designer may wish to suppress, and it does not significantly affect the intended signal. This contribution focuses on analyzing different nanocrystalline (NC) EMI suppressors' performance intended for attenuating interferences in cables. Some NC novel samples are characterized and compare to MnZn and NiZn cores to determine this novel material's effectiveness compared to the conventional ceramic solutions by analyzing samples with different dimensions.

**Keywords:** electromagnetic interference (EMI) suppressors, electromagnetic compatibility (EMC), nanocrystalline (NC), cable filtering, relative permeability, impedance, insertion loss

## 1. Introduction

Electromagnetic interference (EMI) can be defined as electromagnetic signals that unintentionally disturb an electrical or electronic system's normal operation. These perturbances can affect the electrical or magnetic magnitudes (voltage, current or electromagnetic field) of its circuits.

The problem of interferences is an issue that design engineers continually face [1]. Electromagnetic interferences can cause different kinds of problems in digital and analog systems, leading to malfunctions, system reboots, or even permanent damage to the system if the system is not adequately designed or protected [2]. The security of an electronic system in which coexist devices that produce electromagnetic interference and small signal circuits that can sensitive to these disturbances, depends on the compatibility of the signal levels used.. Thereby, it is convenient to comply with specific design and installation rules that allow making the disturbance levels generated by the interferences source elements compatible with the signal levels used by the possible victim elements or elements sensitive to such interferences [3].

Some standards establish the maximum limits of interferences to ensure that the equipment is compatible and does not interfere. Thus, electromagnetic compatibility (EMC) is the ability of a system to operate satisfactorily in its electromagnetic environment without introducing disturbances above the normalized limits in that environment and withstanding those produced by other equipment. Electromagnetic compatibility is regulated by standards that require compliance with the limits of electromagnetic interferences in electronic systems by studying all the phenomena of generation, propagation, and susceptibility to EMI. Thereby, it is necessary to carry out measurements to certify that this equipment complies with regulations to meet these electronic equipment requirements.

When analyzing an EMI problem, the following elements should be identified (**Figure 1**): the source of interferences, the path of propagation, and receivers affected by the interferences. Based on this concept, when a designer faces an EMI problem, he/she must analyze the system, identify these three elements, and deal with interferences applying these strategies: eliminate EMI sources, increase the EMI immunity of the victim element and/or decrease the energy transmitted through the propagation path.

EMI can spread through different means or paths, as shown in **Figure 2**, so they can be grouped into:

- Conducted interference: when the propagation path is an electrical conductor that joins the sources with the affected receiver such as power cables, signal cables, metal chassis.

- Radiated interferences: they can be classified as far- or near-field depending on the propagation's wavelength and the distance between the source and victim elements. Radiated far-field interferences are identified when carried out through electromagnetic fields, fulfilling the following condition: propagation distance > wavelength/2π. Radiated near-field interferences are called coupling and can be identified as inductive coupling or capacitive coupling between neighboring conductors, depending on whether the interference is propagated by a magnetic or electric field, respectively.

The most appropriate strategy is to consider electromagnetic compatibility during the system design stage. If EMC is ignored until the problem arises during the first functional tests or product certification, the solutions usually result in a higher cost [4]. The possibility of applying specific techniques for the elimination of interferences is reduced as a system is developed. At the same time, the cost of EMI reduction increases [5]. However, it is not always possible to predict EMI problems during the design stage because it is complicated to emulate the real environment in


**Figure 1.**
*Main elements in electromagnetic interference phenomena.*

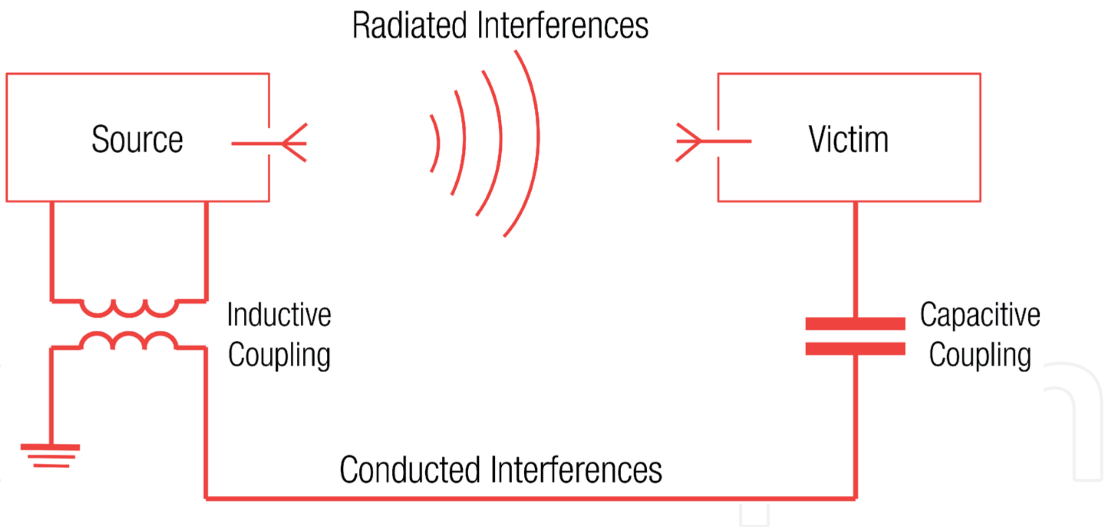


**Figure 2.**
*Kind of propagation and coupling of electromagnetic interference.*

which the system will work. Another possibility is that the designed system complies with the standards, but the problems appear when interconnected with other equipment or facilities. When this situation occurs, the right approach is to suppress EMI at its source whenever possible, rather than increasing immunity through victim circuit protections. This technique works best since a single EMI source can find multiple spread paths and affect different victims. If it is not possible to act directly on the source, it is recommended to focus on the EMI propagation path or, finally, on the affected receiver.

Detection and correct characterization of the EMI is an essential factor in designing a suitable solution. Thus, it is essential to perform EMI measurements using different instrumentation, measuring probes, and antennas to detect the electromagnetic fields that can provide information to the designer from undesired signals. These measurements make it possible to detect the disturbances' magnitude and localize their frequency range in order to select the most optimal solution.

When the cables represent the EMI source, it could not pass the conducted or radiated emissions test. A widely used technique to reduce these problems is applying an EMI suppressor such as a sleeve core [5].

This contribution focuses on analyzing different nanocrystalline (NC) EMI suppressors' performance intended for attenuating interferences in cables. Firstly, some applications of this kind of EMC components are described in section 2, while the description of the manufacturing process and main features of NC material are explained in section 3. The characterization methods employed to determine the NC samples' effectiveness from the standpoint of the impedance and insertion loss they can provide are shown in section 4. Subsequently, in section 5, NC sleeve cores' performance is discussed and compared to conventional ceramic samples. Finally, the main conclusions are summarized in section 6.

## 2. Applications of EMI suppressor sleeve cores

The Magnetic Field (H) is associated with electrodynamic phenomena and appears whenever there are electric currents. The H field can produce effects capable of seriously disturbing the operation of an electronic circuit. Whenever current flows in a circuit, this current creates a magnetic field in that circuit, which will vary as the current varies. Consequently, in any circuit that carries an alternating current, variations of magnetic flux occur. According to Lenz's law, an electromotive force will be induced by the field variation. Therefore, if the current is constant, there will be no induced electromotive force.

Considering that the flux density (B) is proportional to the product of the permeability of the medium and the incident H field, B is the result of the action of H in a magnetic circuit, and its intensity will be higher or lower depending on the permeability of the matter ($\mu_r$). For the shielding of conductors against EMI, the most common is to use ferromagnetic materials since they present a permeability much higher than that of vacuum ($\mu_0$).

When introducing the sample, the external field deforms considerably, being, at each point, the resultant of the initial magnetic field and the field created by the orientation of the magnetic domains. As shown in **Figure 3**, the material concentrates the field lines and regions outside and close to the material, reducing the emitted field.

As explained above, unexpected EMI sources in cables can appear in our system when connected to another device. One of the most used techniques for reducing cables' interferences is applying an EMI suppressor such as sleeve cores to them. This EMI suppressor provides selective attenuation of undesired interference components that the designer may wish to suppress and it does not affect the intended signal. Thereby, this component is widely used to filter EMI in power cables to reduce high-frequency oscillations generated by switching transients or parasitic resonances within a circuit, and EMI in peripheral cables of electronic devices such as multiconductor USB or video cables.

From the standpoint of the magnetic properties, a sleeve core is defined by the relative permeability since it is the main parameter that describes the performance of a specific magnetic material to concentrate the magnetic flux in the core. This parameter is generally expressed through its complex form represented by the real component ($\mu_r$') that quantifies the real or inductive part and the imaginary or resistive component ($\mu_r$") that is related to the material ability to absorb the electromagnetic interferences [6, 7].

The presence of noise current in a conductor generates an undesired magnetic field around it, resulting in EMI problems. The effectiveness of a sleeve core to reduce EMI in cables is defined by its capability to increase the flux density of a certain field strength created around a conductor. Thereby, noise current generates a magnetic field which is concentrated into magnetic flux inside the ferrite by the core's magnetic permeability ($\mu_r$'). This magnetic field inside the ferrite is reduced by the ferrite's magnetic loss ($\mu_r$"), converting it into heat energy. As a result of these two filtering mechanisms the flowing noise current in the conductors is reduced.

Currents that flow in cables (with two or more conductors) can be divided into differential mode (DM) and common mode (CM) depending on the directions of propagation. Although DM currents are usually significantly higher than CM currents, one of the most common EMI radiated problems is originated by CM currents

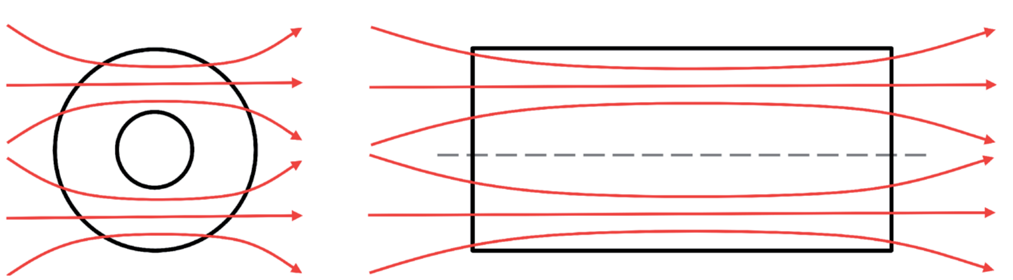

**Figure 3.**
*Management of H field through introducing a sleeve core.*

flowing through the cables of the system [8]. CM currents have a much greater interfering potential, despite not having a high value. This fact is due to only a few microamps are required to flow through a cable to fail radiated emission requirements [5, 9]. The use of sleeve cores is an efficient solution to filter the CM currents in cables because, if a pair of adjacent conductors is considered, when the cable ferrite is placed over both signal and ground wires, the CM noise is reduced. As shown in **Figure 4**, the CM currents in both wires flow in the same direction, so the two magnetic fluxes in the cable ferrite are added together, and the filtering action occurs in the sleeve core. The intended (DM) current is not affected by the presence of the cable ferrite because the DM current travels in opposite directions and is transmitted through the signal and returns. Thus, the current of the two conductors is opposing, meaning they cancel out and the cable ferrite has no effect [10, 11]. In the case of wanting to filter the DM currents, it would be necessary to use a sleeve core in each of the cable's conductors.

An external power supply (**Figure 5**) can be considered a specific example of the application of sleeve cores to reduce EMI in terms of both radiated and conducted emissions. Within the conducted emission range (150 kHz – 30 MHz), the conductors of the system are generally too short to be considered an EMI antenna source since the impedance of possible parasitic inductors is low, and the impedance of parasitic capacitors is typically high. Nevertheless, in the radiated emissions range (from 30 MHz), the parasitic associated with conductors and power line EMI filters can be significant if conductors are long enough to be considered an unintended antenna [12, 13]. External power supplies typically incorporate discrete inductors, capacitors in the AC input circuitry to implement common mode, and differential mode filters before the input bridge and the switching stage. This filtering stage's main objective is to attenuate the interferences that can be conducted out from the power supply to the AC input power lines. Accordingly, the internal PCB is designed to hold these filtering components in order to pass regulatory safety and EMC testing. When these techniques are considered, a power supply design may meet conducted and radiated emission requirements when tested in isolation. Nevertheless, when the power supply is added to a complete system, the system may fail emissions testing due to the interferences emitted from the system load to the

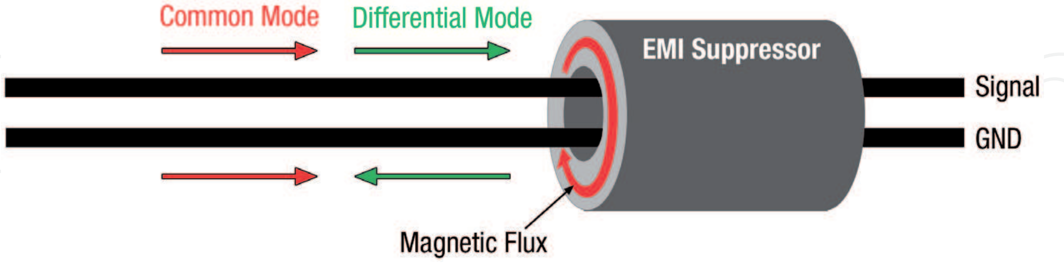


**Figure 4.**
*Diagram of CM and DM currents passing through a cable ferrite with two adjacent conductors (signal and return paths).*

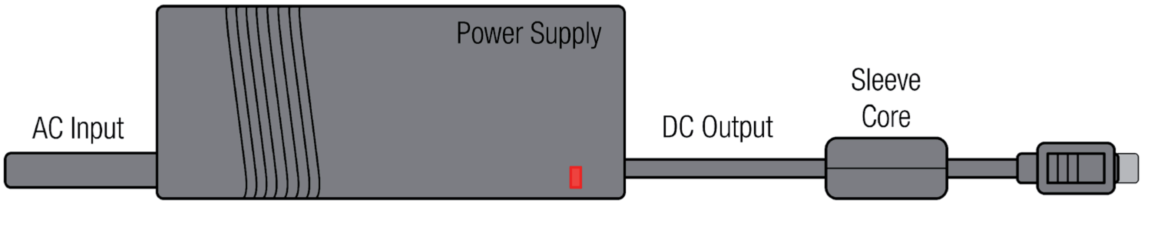


**Figure 5.**
*Diagram of an external power supply elements.*

designed power supply through the DC output cable back. One of the most common solutions to solve this EMI problem is integrating a sleeve core that reduces the undesired interferences without affecting the DC intended signal.

The advantage of using this EMI solution is that it does not involve redesign the electronics and, generally, the mechanical redesign. This is an important advantage because determining in the testing stage, which is the EMI source, may not be straightforward. However, the use of a sleeve core involves adding an extra component whose drawbacks result in increasing the product's size and weight besides the cost of the filtering component and its installation. Therefore, this is an effective solution to attenuate EMI emissions in cables when it is not possible to solve the problem through a system redesign, but it is essential to strike a balance between performance and other factors such as weight, dimensions, and cost [14].

Sleeve cores are manufactured with magnetic material that allows them to control interferences in a certain frequency range with a specific ratio. The values of these two parameters mainly depend on the EMI suppressor intrinsic composition and internal structure. The most used sleeve ferrite cores are based on ceramics or polycrystalline materials because they contain metal oxides, such as manganese or zinc oxide [15]. Thereby, MnZn and NiZn are the most popular EMI suppressor solution due to their heat resistant, hardness, and high resistance to pressure. One of the ceramics' main advantages is the possibility of manufacturing samples with many different shapes able to provide a significant performance [16, 17]. The starting material of ceramics is iron oxide $Fe_2O_3$ mixed with one or more divalent transition metals, such as manganese, zinc, nickel, cobalt, or magnesium [18]. Nanocrystalline sleeve core represents an innovative and increasingly used solution for EMI suppression in cables. This solution has demonstrated excellent suitability to reduce interferences from the low-frequency region to the mid-frequency range [19, 20]. In this sense, some researchers have investigated the use of NC structure compositions to make EMC components because this kind of core can reduce its volume by 50–80% and yield greater magnetic properties and insertion losses than conventional ceramic components [21–24].

Consequently, some NC novel samples are characterized and compare to MnZn and NiZn cores to determine this novel material's effectiveness compared to the conventional ceramic solutions by analyzing samples with different dimensions.

## 3. Nanocrystalline core description

The manufacturing procedure of ceramic materials (**Figure 6**) is based on, firstly, mixing raw materials into the desired proportions. Next, it is then pre-calcined to form the ferrite. The pre-sintered material is then milled to obtain a specific particle size. Subsequently, the granulated material is shaped by a pressing technique to obtain the final form. Finally, the resultant core is sintered, promoting any unreacted oxides to be formed into ferrite and protected with epoxy [25, 26]. The manufacturing procedure and the material mix are essential to define a ceramic core's magnetic properties. Thereby, MnZn materials can provide a significant performance for EMI suppression applications, covering the range of frequency from hundreds of kHz to some MHz. In contrast, NiZn materials are intended for a higher frequency operation than MnZn, covering from tens of MHz to several hundreds of MHz [16, 19, 20, 27].

**Figure 7** shows two micrographs of the samples obtained using scanning electron microscopy (SEM). In these photographs, it is possible to observe the internal structure and the grain size of MnZn (a) and NiZn (b) ceramic materials.

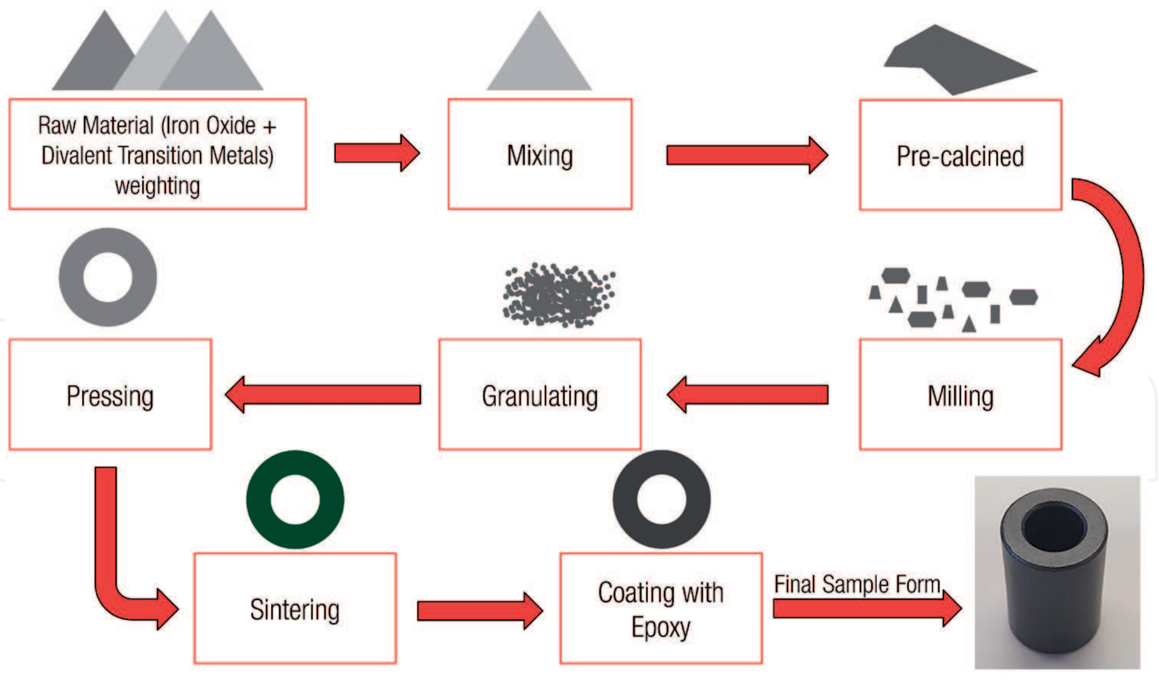


**Figure 6.**
*Diagram of the manufacturing procedure of ceramic cores.*

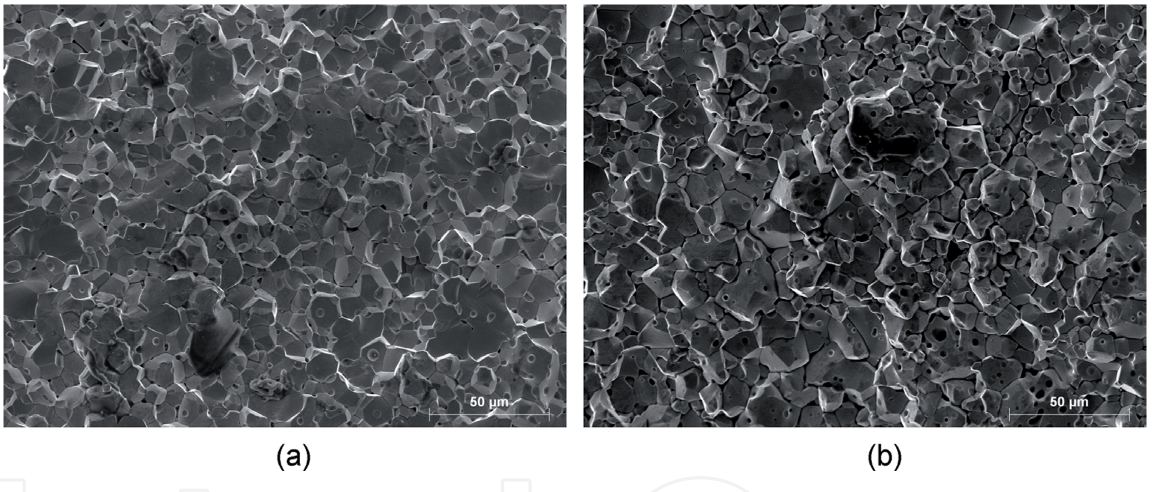


**Figure 7.**
*SEM photographs of ceramics core materials: (a) MnZn material composition; (b) NiZn material composition.*

The results presented in [19, 20] highlighted the great suitability of NC EMI suppressors to filter electromagnetic interference throughout the frequency band from 100 kHz to 100 MHz. Furthermore, data obtained from its magnetic properties indicate that this EMC solution could also provide good performance in terms of EMI suppression at higher frequencies. The advantages of iron-based nanocrystalline materials lie in the high values of relative permeability, the reduction of the magnetic components' volume, and the stable operation up to high-temperatures. These properties are mainly defined by the manufacturing procedure. The manufacturing procedure of NC samples (**Figure 8**) is quite different from the used for ceramic production since it is formed by a continuous laminar structure that is wound to form the final core. The material is a two-phase structure consisting of an ultra-fine grain phase of FeSi embedded in an amorphous ribbon of 7–25 micrometers in thickness. Firstly, the base material is molten by heating it at 1300 °C and depositing it on a water-cooled wheel that reduces the temperature of the material to 20 °C. Next, the resulting amorphous metal ribbon is exposed to an annealing

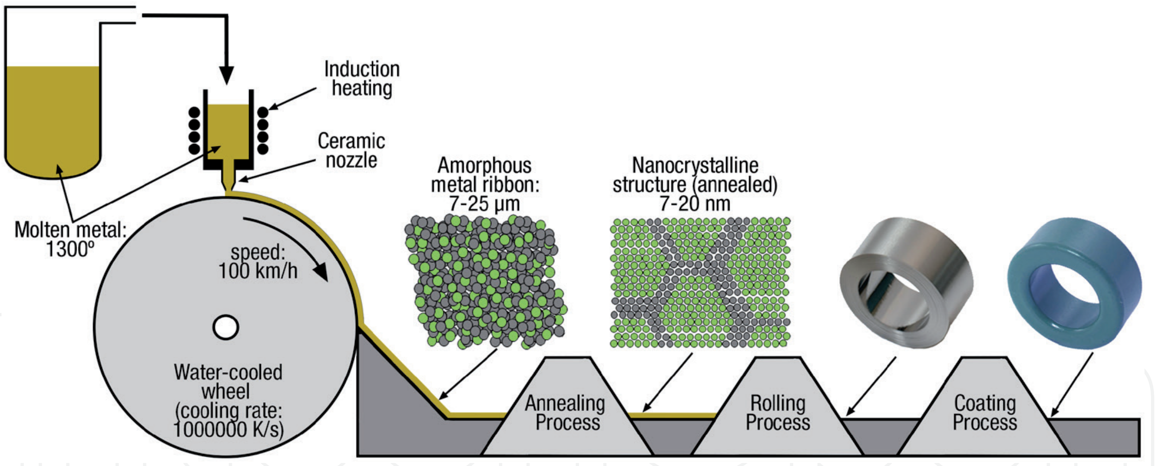


**Figure 8.**
*Diagram of the manufacturing procedure of nanocrystalline cores..*

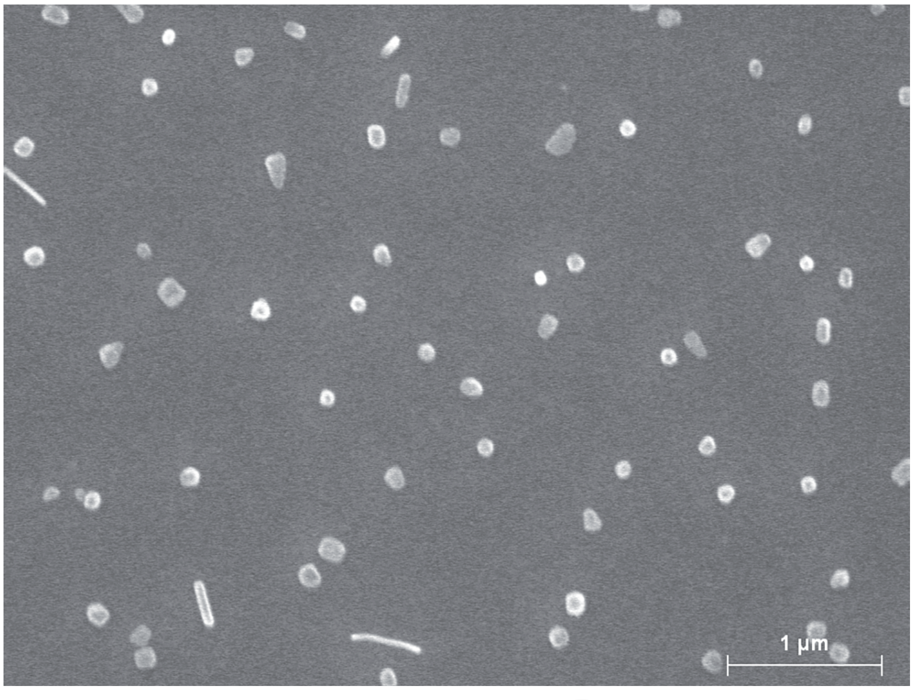


**Figure 9.**
*SEM photograph of a nanocrystalline core material.*

process under the presence of transversal and/or longitudinal magnetic fields. This treatment modifies the magnetic properties and the amorphous structure forms ultrafine crystals with a typical size of 7–20 nm, obtaining the nanocrystalline material. The last stage of this procedure corresponds to applying a protective coating or a plastic housing that protects the obtained cores due to the brittle nature of the tape [11, 18, 28].

**Figure 9** shows a SEM photograph of a NC sample where it is possible to observe the difference in terms of the grain size if it is compared with the ceramic materials since it is in the order of nanometers.

## 4. Characterization methods

The evaluation of NC sleeve cores is carried out by analyzing the performance regarding two MnZn and NiZn ceramic cores. Therefore, the evaluation of the three different solutions in terms of EMI suppression from the standpoint of the magnetic

| Sample reference | Magnetic material | Outer diameter (OD) (mm) | Inner diameter (ID) (mm) | Height (H) (mm) |
|---|---|---|---|---|
| S1 | NC | 15.3 | 5.5 | 20.0 |
| S2 | MnZn | 16.0 | 8.0 | 28.5 |
| S3 | NiZn | 17.5 | 9.5 | 28.5 |
| S4 | NC | 28.3 | 15.5 | 30.0 |
| S5 | MnZn | 26.0 | 13.0 | 28.5 |
| S6 | NiZn | 26.0 | 13.0 | 28.5 |

**Table 1.**
*List of sleeve core samples analyzed.*

properties, the impedance, and the insertion loss provided by different samples. One of the cores selected is based on MnZn, a material widely used to reduce EMI in the low-frequency region and the other selected core is made of NiZn that is generally employed to filter EMI from some tens of megahertz. Thus, it is important that the analyzed sleeve cores have a similar volume in order to conclude which solutions is more effective depending on the frequency range selected. Accordingly, different ceramic MnZn and NiZn sleeve core samples with similar dimensions to the NC samples have been selected to be characterized and evaluated, as shown in **Table 1**. Note that two sets of three different materials are analyzed. In the case of the small samples set (S1, S2, and S3), the ceramic samples are longer than the NC one, whereas in the large samples set (S4, S5, and S6), the three cores have similar dimensions.

### 4.1 Relative permeability

The relative permeability ($\mu_r$) is one of the most important parameters that define the material's ability to absorb electromagnetic interferences. The permeability relates the magnetic flux density of a specific magnetic field in a defined medium. When a sleeve core is placed around a certain cable, it concentrates the magnetic flux. The material's internal properties describe its ability to focus the magnetic flux is represented through the permeability complex parameter. The effectiveness to attenuate EM interferences of a material can be quantified by separating μr into its complex form. The real component is related to the stored energy or inductive part (μ') and the imaginary component that provides the losses or resistive part (μ"). Thereby, the complex relative permeability is expressed by:

$$\mu_r(f) = \mu'(f) - j\mu''(f) \tag{1}$$

The magnitude of the NC material's relative permeability is represented together with MnZn and NiZn permeability traces in **Figure 10** to study the frequency region covered by each material. This graph shows the NC core provides higher permeability than the ceramic materials throughout almost the entire frequency range studied, despite being the material with higher initial permeability. MnZn has an initial permeability ($\mu_i$) of 5000 and it is able to provide a permeability around 3000 up to the 2 MHz, providing a similar value to NC at this frequency point. NC demonstrates the best performance in the mid-frequency region, whereas the NiZn material ($\mu_i$ = 620) is more effective in the high-frequency region. The NC material has an initial permeability ($\mu_i$) of 30000 and it provides a significant permeability up to 200 MHz.

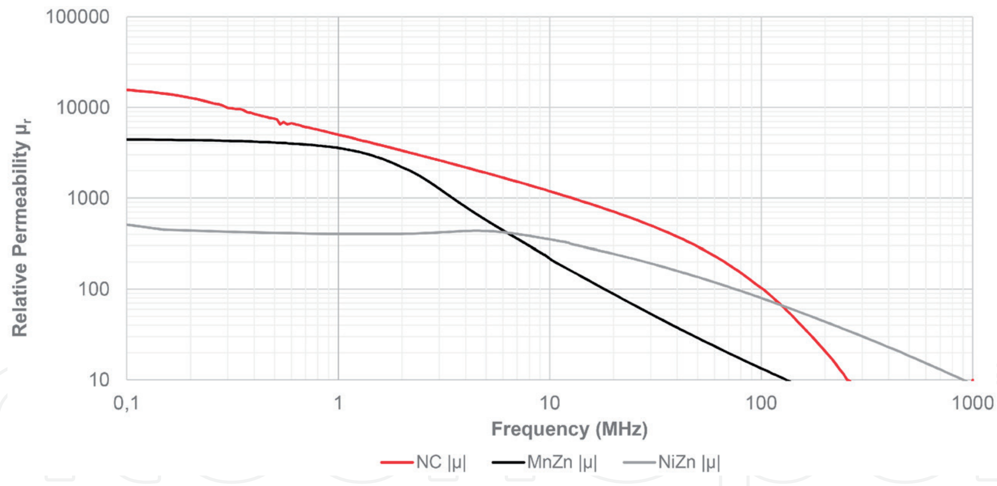


**Figure 10.**
*Relative permeability of NC core compared to MnZn and NiZn compositions.*

### 4.2 Impedance parameter

The permeability parameter is used to describe the core material's behavior; however, manufacturers of EMI Suppressors generally provide their customers the impedance that it introduces in the cable in which it is applied. Typically, the datasheets only specify the impedance at several frequency points or the graph of the magnitude of the impedance in the frequency range where it is more effective. The impedance of a certain sleeve core considers, besides the material permeability, other variables such as the self-inductance defined by the dimensions and the shape. Thereby, sleeve cores are usually defined and classified by specifying the magnitude of the impedance ($Z_F$), which is obtained from the equivalent component parameters such as resistance (R) and the impedance of the inductive part ($X_L$). The magnitude of the impedance is given by:

$$|Z_F| = \sqrt{R^2 + (X_L)^2}. \tag{2}$$

The measurement of the impedance carried out in this contribution has been performed by using the E5061B Vector Network Analyzer (Keysight) connected to the Terminal Adapter 16201A (Keysight) and the Spring Clip Fixture 16092A (Keysight), as shown in **Figure 11**. These fixtures are internally compensated by an impedance standard calibration method to consider the electrical length path and the impedance variations caused by parasitic elements.

### 4.3 Insertion loss parameter

Another kind of EMC component datasheets, such as common-mode-chokes, show the attenuation ratio or insertion loss in terms of decibels (dB) that are able to provide. In the case of sleeve cores, it is also possible to determine the insertion loss that it introduces when applied in a cable. The insertion loss that a sleeve ferrite core is able to yield is strongly dependent on the impedance of the system in which it is placed, besides its impedance response depending on the frequency. Subsequently, these components are more effective against EMI when the source and load systems' impedance is low. The equivalent circuit approach to determine the insertion loss parameter of a specific sleeve core requires considering the source impedance ($Z_A$) and the load impedance ($Z_B$) of the system with electromagnetic interference

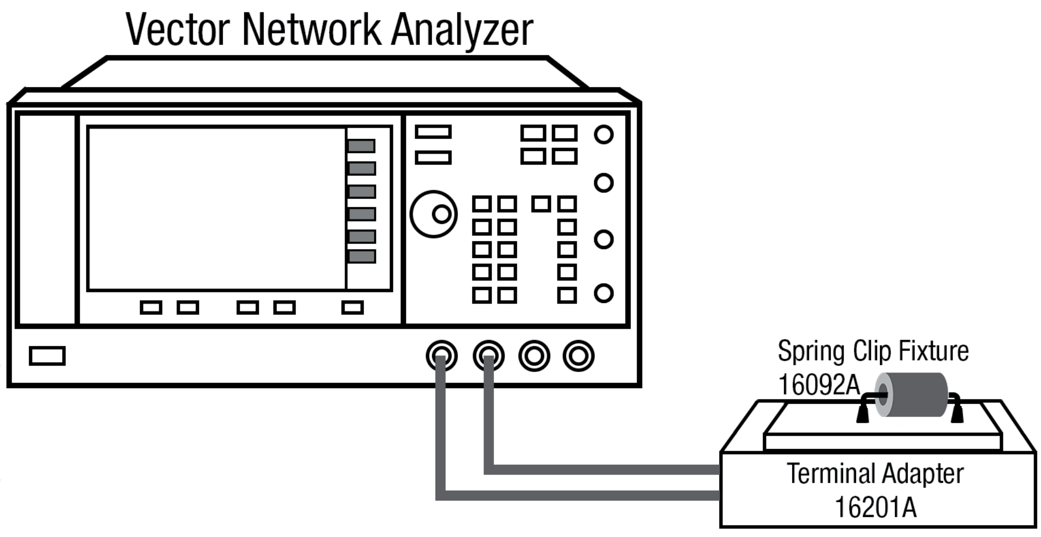


**Figure 11.**
*Setup for measuring impedance of sleeve core samples.*

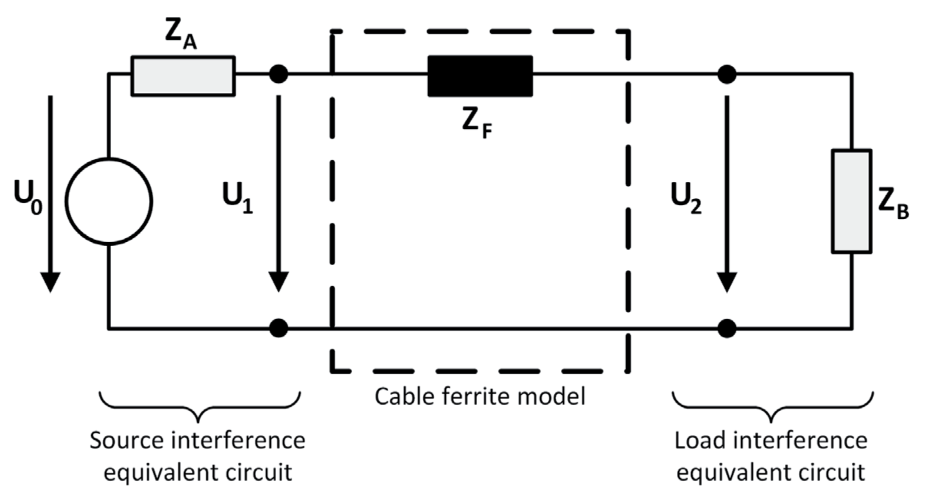


**Figure 12.**
*Schematic of source and load equivalents circuits used to determine the insertion loss parameter of a sleeve core when introduced into a system.*

problems. The impedance introduced by the sleeve core ($Z_F$) in that system is introduced in the path that connects both systems. The equivalent circuit diagram employed to determine this impedance relation and analyze the effect of introducing a sleeve core into a certain system is shown in **Figure 12** [29].

According to this diagram, when the system impedance is known, the insertion loss (A) in terms of decibels can be calculated through the Eq. (3) considering the impedance of the sleeve core ($Z_F$):

$$A(dB) = 20\log\left(\frac{Z_A + Z_F + Z_B}{Z_A + Z_B}\right) \tag{3}$$

## 5. Results and discussion

The results presented in this section correspond to the analysis of the performance provided by NC samples compared to ceramic solutions. This comparison is carried out by evaluating both the impedance and insertion loss parameters described in the previous section. Two sets of three sleeve cores are analyzing to study the performance provided by samples intended for thin cables (samples S1, S2, and S3) and those with larger diameters (samples S4, S5, and S6). These results make it possible to observe the performance of each EMI suppression solution. It allows the system designer to select the best component to solve EMI problems depending on the frequency range where it is located.

Firstly, the impedance measured of the two sets of samples is shown in **Figures 13** and **14**. **Figure 13** shows the response of the three small samples and it can be observed that the MnZn sleeve core is able to provide the best performance in the low-frequency, achieving its maximum value at 1.5 MHz (132.08 Ω). NiZn sleeve core reaches the maximum impedance value at 50.1 MHz (145.63 Ω). This material represents an interesting solution to reduce EMI in the mid and high-frequency regions, whereas it does not provide a valuable impedance in the low-region. NC sample offers the highest impedance values in the mid-frequency region (from 4.1 MHz to 95.6 MHz), reaching the maximum impedance value at 34.9 MHz (162.04 Ω).

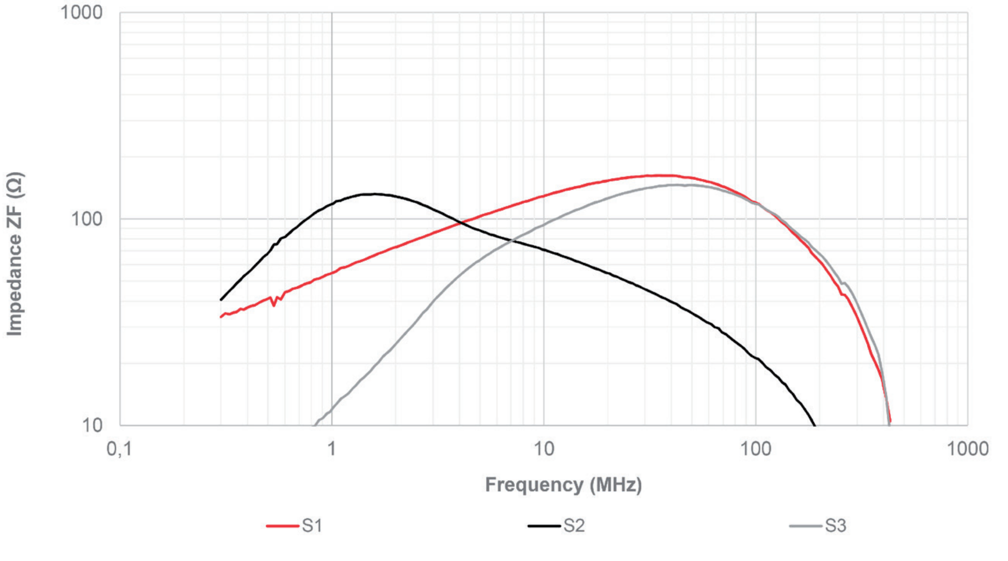


**Figure 13.**
*Magnitude impedance of the NC (S1), MnZn (S2), and NiZn (S3) samples.*

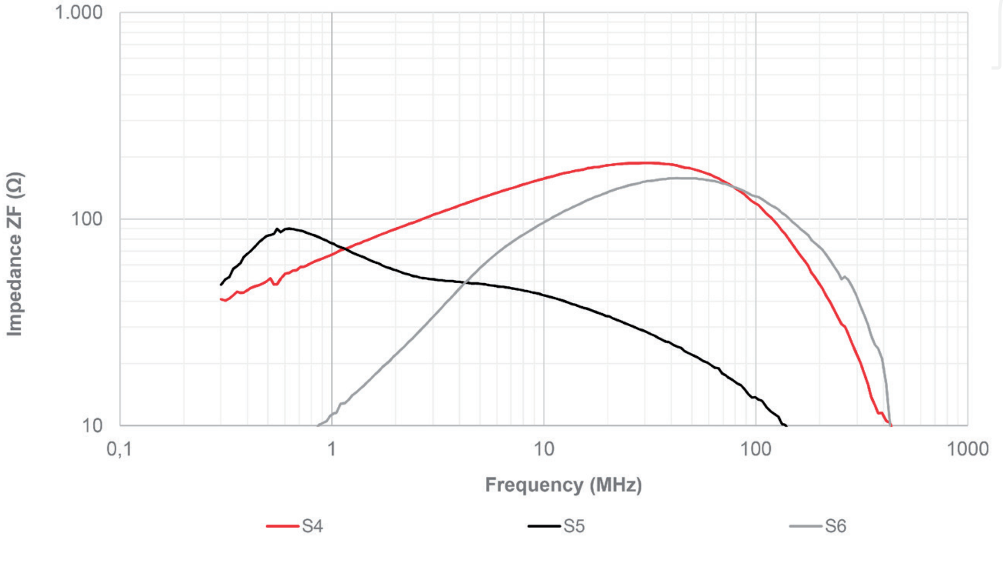


**Figure 14.**
*Magnitude impedance of the NC (S4), MnZn (S5), and NiZn (S6) samples.*

Nevertheless, in contrast to ceramic materials, NC sample is able to provide a significant response in both the low and high-frequency region. NC sleeve core shows a better performance than ceramics to reduce EMI emissions in a wideband frequency range.

**Figure 14** shows the performance of the large sleeve core samples in terms of the impedance response. It is possible to observe that the MnZn sample is the most effective solution to reduce interferences up to 1.2 MHz. From this frequency value, the NC sample is able to introduce a higher impedance value than the other two solutions, covering the range from 1.2 MHz to 77.7 MHz. NiZn sample provides larger impedance than NC in the high-frequency region. The maximum impedance value offered for the MnZn sample is located at 0.6 MHz (89.55 Ω). In the case of the NC sample, this value is achieved at 33.1 MHz (186.77 Ω), whereas the NiZn sample reaches the highest impedance value at 48.2 MHz (157.49 Ω). It is possible to observe that the frequency ranges where the large sleeve core is most effective are similar to the provided by the small samples. In **Figure 14**, the MnZn sample (S5) shows a less significant performance than the smaller sample response based on the same material (S2). The dimensional effect causes this shift in the resonance frequency (maximum impedance value). Thereby, MnZn material reduces its performance when it is used to manufacture large cores due to its internal structure and electrical features. Nevertheless, it is possible to observe that the dimensional effect does not affect the NC and NiZn material when used to manufacture large EMI suppressor cores. However, despite these aspects, the effectiveness in the different frequency regions is similar to the described for the last set of samples.

The insertion loss results have been obtained by considering a system with an input and output impedance of 50 Ω ($Z_A$ = $Z_B$ = 50 Ω). Thereby, the experimental results that are shown in **Figures 15** and **16** can be compared by considering Eq. (3) and the impedance provided by each sleeve core ($Z_F$). The results obtained in terms of insertion loss correlate with the impedance responses shown previously since MnZn samples provide a higher attenuation ratio in the low-frequency region. Specifically, the S2 sample provides up to −7.25 dB at 1.7 MHz and − 5.43 dB at 0.6 MHz in the case of S4. Thereby, MnZn material represents the best solution when the interferences are located below 4.2 MHz, considering the small sample set (see **Figure 15**). This frequency range is reduced when larger samples are analyzed since the MnZn S4 sample predominant frequency range

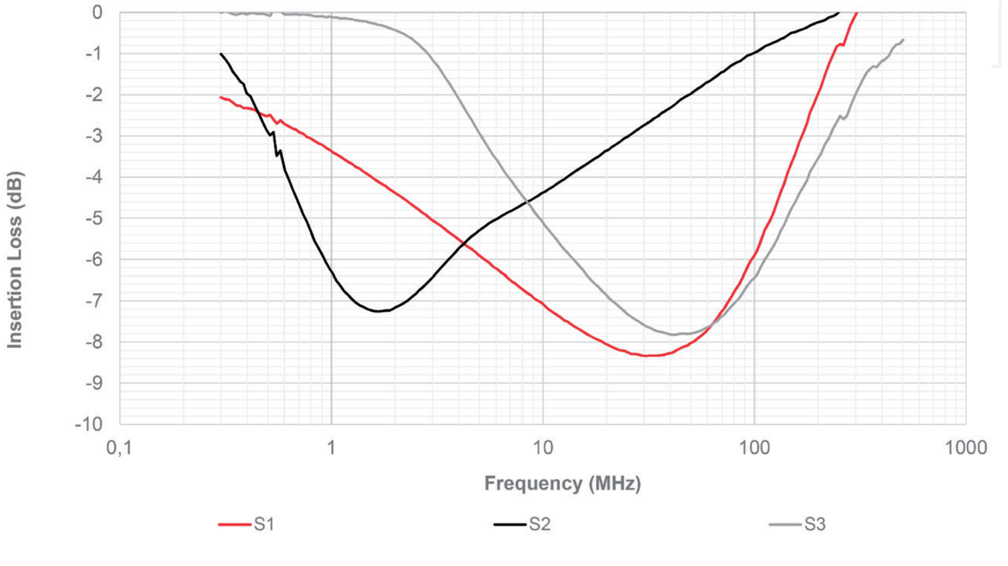


**Figure 15.**
*Insertion loss of the NC (S1), MnZn (S2), and NiZn (S3) samples.*

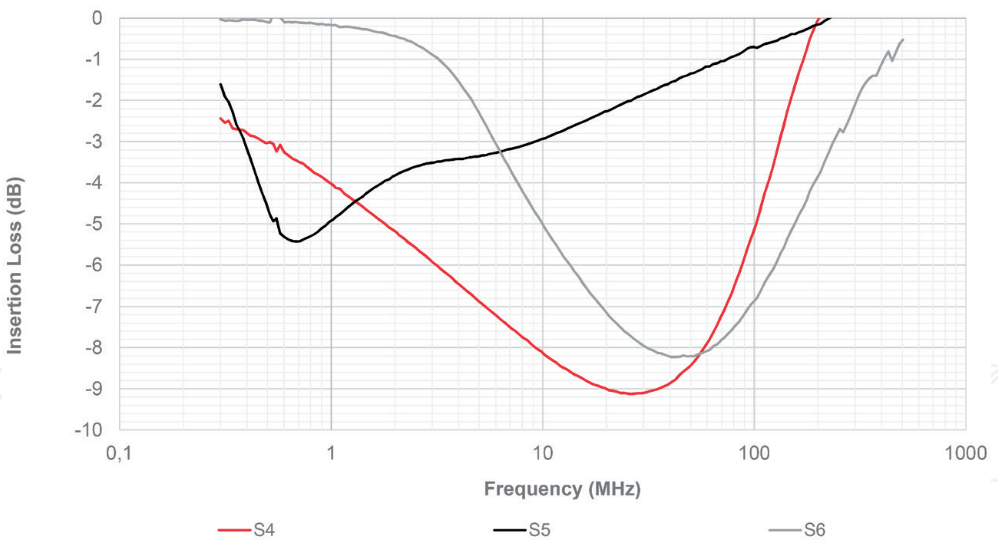


**Figure 16.**
*Insertion loss of the NC (S4), MnZn (S5), and NiZn (S6) samples.*

is shorter up to 1.3 MHz if compared to the NC S3 sample (see **Figure 16**). As a result of this, the effectiveness of MnZn material is reduced compared to NC material when the dimensions of the sample are increased, since the S4 sample's frequency range is shorted 3.9 MHz and the maximum attenuation has been reduced 1.82 dB. Considering this behavior of MnZn material when a large core is employed, NC represents an alternative solution to suppress EMI in the low-frequency region when a large sleeve core is needed due to it provides higher attenuation than NiZn in this range. Regarding the mid-frequency region, NC samples (S1 and S4) have a similar response, reaching the maximum values of insertion loss at 33.5 MHz (−8.33 dB) in the case of S1 and 28.2 MHz (−9.11 dB) for S4. NC S1 sample has the predominant response from 4.2 MHz to 60.4 MHz, considering the small sample set (see **Figure 15**) and from 1.3 MHz to 57.2 MHz in the case of the large samples (see **Figure 16**). NiZn S3 and S6 samples are able to offer the best performance in the high-frequency region since NC samples have a resonance frequency lower than the value shown by NiZn cores. This insertion loss difference between NC and NiZn in the high-frequency region is more significant when the large sample cores.

Consequently, MnZn samples are significantly effective in the low-frequency region, but their performance is strongly reduced in the high-frequency region. Contrary to this behavior, NiZn samples show great insertion loss in the high-frequency region, whereas it provides a poor performance in the low-region. However, NC samples show the best performance in the mid-frequency region at the same time that it provides a significant insertion loss in the low-frequency region and a comparable response than the offered by the NiZn samples in the high-frequency region.

Note that these results are related to the impedance of both systems where the cable in which the sleeve core is applied. Therefore, the insertion loss values obtained can be considered when the EMI suppression solution is applied to data or video cables. According to Eq. (3), if these samples were installed in power cables, it could be possible to obtain higher attenuation ratios. For instance, if the sleeve core is installed in a system where $Z_A = Z_B = 5\ \Omega$, the $Z_F$ provided by the sample is more significant than the system impedance. Thereby, if the maximum impedance provided by S1 is considered ($Z_F = 145.63\ \Omega$) it can be able to introduce an insertion loss of −23.84 dB instead of the −8.33 dB obtained for $Z_A = Z_B = 50\ \Omega$.

## 6. Conclusions

The performance of NC samples has been compared with the effectiveness provided by ceramic cores. Thereby, it has been analyzed the performance of each EMI suppression solution from the standpoint of the magnetic properties, impedance, and insertion loss.

Considering the results presented, it is possible to identify the frequency regions where each material solution is effective to reduce EMI when applied in a certain cable. According to the relative permeability data, the MnZn material analyzed is suitable when the interferences are located in the low-frequency region (from hundreds of kilohertz up to some megahertz). In contrast, NiZn solution is not effective in this frequency region. NiZn samples show an interesting solution to reduce EMI in the mid and high-frequency region since it shows a better response than MnZn up to about 5 MHz. The relative permeability data shows that NC material is able to provide a wideband solution due to it is able to offer a comparable response to MnZn material in the low-frequency region and NiZn material in the high-frequency region. Furthermore, NC shows the highest permeability in the mid-frequency region. The excellent magnetic properties shown by the NC material have been verified from the standpoint of the impedance and the insertion loss that the NC samples can introduce in a certain cable with electromagnetic disturbances. Therefore, MnZn samples show a significant performance to reduce EMI in the low-frequency region in terms of impedance and insertion loss, whereas NiZn is effective against high-frequency interferences.

Consequently, if the EMI disturbances are specifically located in the low or high-frequency region, a ceramic core is able to provide significant effectiveness to reduce them. If the interferences are detected in the mid-region (from 5 MHz to 100 MHz), NiZn material is able to provide better performance than MnZn if only ceramic cores are considered. NC structures usually represent a higher cost than ceramic, so that this solution may not always be considered to solve an EMI problem located in a specific frequency region. This is the reason why a designer could select a ceramic core instead of a NC core to reduce an EMI problem despite the ceramic core could not be the most effective solution. Nevertheless, when the EMI disturbances are distributed in different frequency regions, NC sleeve core shows a better performance than ceramics to reduce EMI emissions in a wideband frequency range.

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