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Efficiency Analysis of Simple Structures of Ferrite EMI Suppressors in Different Ferrite Materials

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Invited Paper

The properties of ferrite material as well as geometrical parameters determine the efficiency of ferrite component in electromagnetic interference (EMI) applications. Due to the presence of ferrite material, EMI suppressor behaves as low pass filter (i.e. as a frequency dependent resistor) and provides signal free from distortions. Near ferrimagnetic resonant frequency, component has maximal impedance and efficiently suppresses noise. Better suppression can be achieved by making the conductive layer longer. Three simple structures are analyzed: Line, Zig-zag and Double coil. Nevertheless, longer conductive lines introduce parasitic capacitance, which causes the maximal impedance frequency shift towards lower frequencies. The aim of this paper is to investigate the efficiency of simple structures of EMI suppressors in different ferrite materials. Two Ni-Zn materials are used for fabrication of EMI suppressors: low permeability F14 material (suitable for suppression above 200 MHz; initial permeability $\mu_r = 220$), and high permeability F19 material (which is used for suppression in the range from 20 MHz to 200 MHz; $\mu_r = 1000$). Comparison of the same structure with identical geometrical parameters in F14 and F19 material in the frequency range 1 MHz–3 GHz shows that the device in low permeability F14 material achieves greater impedance and better suppression (up to 25 %).

1. Introduction

Significant achievements in ferrite material processing provide a whole new range of ferrite materials which can have permeability up to 30.000 or frequency range up to several gigahertz [1]. That progress enables developments of many ferrite devices with a wide range of power levels and working frequencies [2]. Today ferrite components play important role in power electronics area, telecommunications, consumer electronic, automotive etc.

One of the major applications of ferrite components is in the field of electromagnetic interference (EMI) suppression. With the increasing amount of electronic equipment being used together in areas where they can affect each other, the probability of EMI becomes higher. Because of that, the electromagnetic compatibility (EMC) regulations which specify the limits of the interference level caused by the equipment and/or the sensitivity of equipment to the incoming interference are becoming more stringent every day [3], [4].

During the design phase, problems with interference can be avoided to some extent. Often additional suppression components such as inductors, capacitors or a combination of both will be necessary to meet the required levels. Ferrite EMI suppressors are very effective in elimination of unwanted signals when configured in series with a noise producing circuit, especially in high frequencies. They are usually used for EMI suppression in universal series bus, low-voltage differential signaling and in other high-speed digital interfaces incorporated in notebooks and PCs, digital cameras, etc. They have impedances between 6 Ω and 2000 Ω at 100 MHz and typical suppression frequency range from 10 MHz to 1 GHz, while rated currents are between 0.1 A and 6 A [5]-[7].

For EMI suppression design ferrites are mostly used, especially Ni-Zn and Mn-Zn materials. Ni-Zn materials have lower initial permeability than Mn-Zn (up to 1000), but they maintain their permeability in wider frequency range (> 100 MHz). By reason of that, they will not produce high impedance at low frequencies and can be used for suppression at frequencies over 20 MHz [6].

Permeability is one of the most important parameters used in evaluating magnetic materials. Not only is it a function of the chemical composition and crystal structure but it is strongly dependent on microstructure, temperature, stress, time after demagnetization and several other factors [1]. At high frequencies, the permeability μ_r is a complex parameter consisting of a real μ_r' and imaginary part μ_r'', $\mu_r=\mu_r'-j\cdot\mu_r''$. Both parts of the permeability are frequency dependent.

Therefore, ferrite materials introduce into circuit frequency-dependent impedance and inductance and strongly determine the possible application of ferrite components. In order to design an electrical circuit with best performance, designers have to select appropriate ferrite components and materials regarding their parameters (primarily permeability and magnetic loss tangent) and to know their behaviour in different working conditions. Because of that, a development of electrical equivalent circuit models is crucial for computer-aided design tools in high frequency design practice.

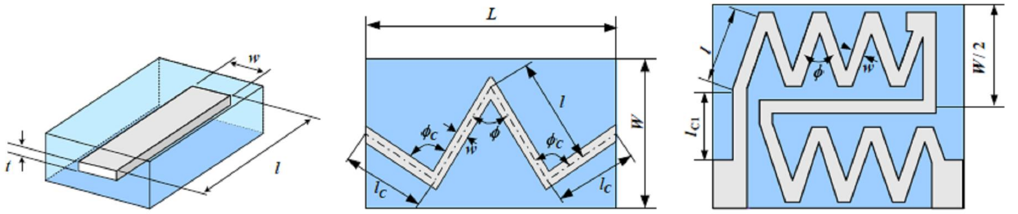
In our previous work [8], Zig-zag structure of EMI suppressor is analyzed. The goal of this paper is to further explore the frequency shift effect and its influence on the efficiency of EMI suppressor if different ferrite materials (F14 and F19 MMG Neosid materials [9]) and structures (Line and Zig-zag) are used.

2. Simple Structures of Ferrite EMI Suppressors

A ferrite EMI suppressor is multilayer component, which consists of a conductive layer embedded in a ferrite monolithic structure. Two Ni-Zn materials are used for fabrication of EMI suppressors: low permeability F14 material (suitable for suppression at high frequencies above 200 MHz; initial permeability $\mu_r = 220$), and high permeability F19 material (which is used for suppression in the range from 20 MHz to 200 MHz; $\mu_r = 1000$) [9]. In the middle of a ferrite body, a platinum conductive layer is embedded to provide low DC resistance of the component ($\rho = 10.6\cdot10^{-8}$ Ωm) [10].

Different conductive layer structures are analyzed: "Line" (length $l = 2.01$ mm, width w, and thickness $t = 10$ μm) and "Zig-zag", which consists of N straight conductive segments. Each two neighboring segments make an angle ϕ, and the angles with two outermost segments are denoted ϕ_C (Fig. 1a). The components have standard EIA size 0805 (2.01 mm × 1.25 mm × 1.1 mm).

In order to achieve better suppression and greater insertion loss (i.e. larger impedance), the conductive layer should be longer. Because of that, the "Double coil" structure have been additionally analyzed. It consists of two Zig-zag coils connected in series (Fig. 1b), size 1210 (3.2 mm× 2.54 mm ×1.1 mm). Nevertheless, a longer conductive line causes the shift of the frequency range in which the component introduces attenuation towards lower frequencies, and designing process should be very careful.



(a) (b) (c)

Fig. 1. (a) The "Line" structure of ferrite EMI suppressor EIA size 0805 (length l = 2.01 mm, width w, and thickness t = 10 µm). (b) The "Zig-zag" structure consists of N straight conductive segments (l = 1000 µm, w = 150 µm and t = 10 µm, EIA size 0805) and two segments leading to contacts (length l_C). (c) The "Double coil" structure consists of two Zig-zag coils in series (l= 950 µm, w= 170 µm, t = 10 µm, EIA size 1210).

3. Impedance Modeling of Ferrite EMI Suppressors

Ferrite components are not easy to model, due to the frequency-dependent and nonlinear ferrite characteristics. The complexity of modelling procedures rises if the component is miniaturized.

The modelling of the ferrite EMI suppressor is based on the partial inductance method. The most important quality of the partial inductance concept is the ability to break a complicated 3-dimensional problem into its constituent interactions [11]. Hence, the segments of the conductive layer are divided into n parallel filaments having small, rectangular cross sections (Fig. 2). Depending on the geometry and current vectors in filaments, the partial self- and mutual inductances were calculated using equations presented in [12].

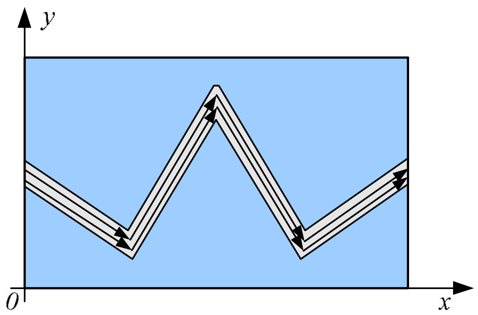


Fig. 2. The partition of straight conductive segments into elementary filaments. Taking care of the current flow, each filament is represented with vector.

The equivalent inductance L is calculated as the sum of the partial self-inductances of all elementary filaments L_i and the sum of mutual inductances between all elementary filaments L_{ij},

$$L = \sum_{i=1}^{n} L_i + \sum_{i=1}^{n}\sum_{j=1}^{n} L_{ij}, \quad \text{where } i \neq j. \tag{1}$$

The equivalent inductance can be also expressed as $L=\mu_r'\cdot L_0$, where L_0 is inductance of the structure in the air.

The equivalent series resistance R is calculated as

$$R = R_{DC} + R_W + R_F\ , \tag{2}$$

where R_{DC} is the total dc resistance, R_W and R_F are the winding and ferrite resistances, respectively. At RF frequencies, the magnetic losses dominate, $R \approx 2\cdot\pi\cdot f\cdot\mu_r''\cdot L_0$.

The stray capacitance C represents the parasitic effects of the conductive layer. The detail calculation of parameters R, L and C is presented in [12].

An accurate description of the frequency response of the EMI suppressor is achieved using a simple equivalent circuit model, which consists of the series connection of the equivalent inductance L and resistance R, in parallel with the stray capacitance C. Using the equivalent circuit model, the total impedance Z can be determined as

$$Z(j\omega) = \frac{R + j\cdot(\omega L(1-\omega^2 LC) - \omega R^2 C)}{(1-\omega^2 LC)^2 + \omega^2 R^2 C^2}\ . \tag{3}$$

Developed simulation tool SPIS (Simulator for Planar Inductive Structures) for calculation of electrical characteristics of ferrite EMI suppressor (i.e. inductance, resistance, reactance, Q-factor and total impedance versus frequency) have been based on this model. The SPIS algorithm is presented with more details in [12].

4. Comparison of Simulation and Measurement Results

The comparisons of measured (dot line) and simulated (solid line) inductance, resistance and impedance for Line and Zig-zag structure in F19 material are presented in Fig. 3 throughout Fig. 5. Realized EMI suppressors were electrically tested in the range of frequencies from 1 MHz to 3 GHz using Agilent 4287A RF LCR meter. Simulated results are obtained by SPIS tool.

As it can be seen in Fig. 3, the geometry of the conductive layer determines the EMI suppressor inductance. If the conductive line is narrower, the inductance will be greater (Line structure 150 μm wide and 10 μm thick in F19 material has L=395 nH at 1 MHz, while wider conductive layer, w=950 μm, has twice smaller inductance L=205 nH). Similarly, the maximal impedance of the narrower conductive line will be greater (line wide 150 μm has Z_{MAX}=47.85 Ω, while 150 μm wide has Z_{MAX}= 25.46 Ω). The main contribution to impedance at high frequencies comes from the resistance R (i.e. magnetic losses, $R \approx 2\cdot\pi\cdot f\cdot\mu_r''\cdot L_0$), as it can be seen in Fig. 4.

Further decrease of conductive layer's cross section will increase L, R and Z, but also proportionally decrease the current carrying capacity of EMI suppressor and therefore should be avoided. It should be noted that the ferrite material permeability determines the shape of these curves ($L=L(f)$, $R=R(f)$ and $Z=Z(f)$), as well as the frequency range where the ferrite device is the most effective. In the vicinity of ferrimagnetic resonance frequency the ferrite EMI suppressor has maximal impedance, $Z \approx j\cdot\omega\cdot L_0\cdot(\mu_r' - j\cdot\mu_r'')$.

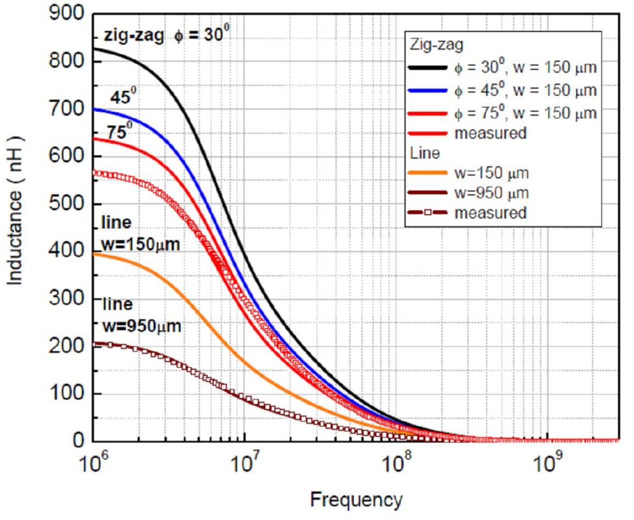


Fig. 3. The inductance of "Line" and "Zig-zag" structure with different angles ϕ and the maximal number of conductive segments N in F19 material (ϕ_1=30º, N_1=7; ϕ_2=45º, N_2=5; ϕ_3=60º, N_3=3; ϕ_4=75º, N_4=2); w=150μm.

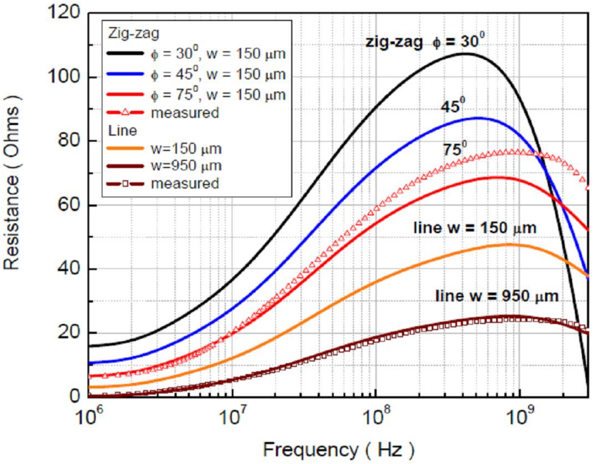


Fig. 4. The resistance of "Line" and "Zig-zag" structure with different angles ϕ and the maximal number of conductive segments N in F19 material (ϕ_1=30º, N_1=7; ϕ_2=45º, N_2=5; ϕ_3=60º, N_3=3; ϕ_4=75º, N_4=2); w=150μm.

In order to achieve even greater impedance and hence better suppression, it is necessary to design the longer conductive layer. To accomplish that goal, yet to have a simple planar structure (which is easy to manufacture), zig-zag or meander shape should be used instead of the straight line.

If the Zig-zag structure has more segments N and if the total length of conductive layer l_{TOT} is longer, the total inductance and impedance will be increased (Table I). However, longer conductive lines introduce parasitic capacitance, which causes the frequency shift of the maximal impedance (Fig. 6). Due to that, the frequency range where component can be used for efficient EMI suppression is shifted towards lower frequencies, and designing process should be very careful.

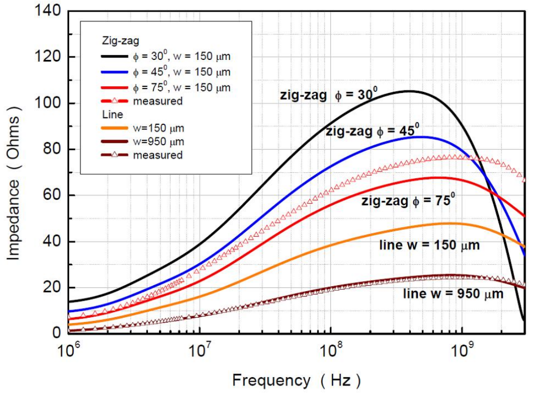


Fig. 5. The impedance of "Line" and "Zig-zag" structure with different angles ϕ and the maximal number of conductive segments N in F19 material (ϕ_1=30º, N_1=7; ϕ_2=45º, N_2=5; ϕ_3=60º, N_3=3; ϕ_4=75º, N_4=2); w=150μm.

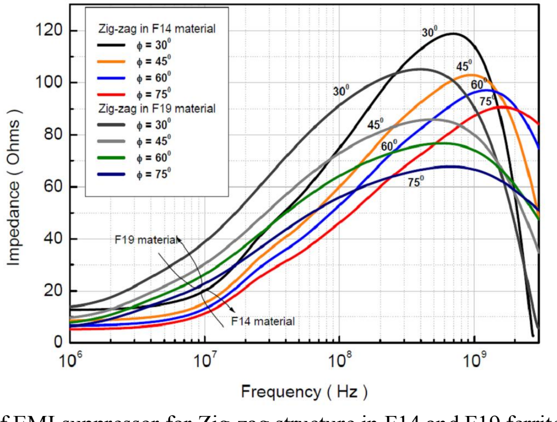


Fig. 6. The impedance of EMI suppressor for Zig-zag structure in F14 and F19 ferrite materials with different angles ϕ and number of segments N (ϕ_1=30º, N_1=7; ϕ_2=45º, N_2=5; ϕ_3=60º, N_3=3; ϕ_4=75º, N_4=2); w=150μm.

The influence of the angle ϕ on the maximal impedance Z_{MAX} and the maximal impedance frequency shift of the ferrite EMI suppressor in F19 material are also presented in Table I. The frequency shift toward lower frequencies can be also seen for F14 and F19 ferrite materials in Fig. 7.

Table I. The influence of the angle ϕ on the maximal impedance Z_{MAX} and its frequency shift of the EMI suppressor in F19 material

Number of segments N	$N = 2$	$N = 3$	$N = 5$
Angle	ϕ = 75°	ϕ = 60°	ϕ = 45°
Contact length	l_C = 750 μm	l_C = 450 μm	l_C = 350 μm
Contact angle	ϕ_C = 85°	ϕ_C = 60°	ϕ_C = 46°
Total length	l_{TOT} = 3.5 mm	l_{TOT} = 3.9 mm	l_{TOT} = 5.7 mm
Inductance at 1 MHz	L = 139.4 nH	L = 156.9 nH	L = 172.2 nH
Maximal impedance Z_{MAX}	67.72 Ω	76.65 Ω	85.36 Ω
Frequency	at 661 MHz	at 565 MHz	at 483 MHz

Note: Other geometrical parameters are identical for all structures (l= 1000 μm, w = 150 μm, t = 10 μm).

5. Discussion

Due to the presence of ferrite material, the inductance, resistance and impedance are highly nonlinear. Although the shapes of dependences $R=R(f)$ and $Z=Z(f)$) are the same for different total length of the conductive layer l_{TOT} (Fig. 4 and Fig. 5), they will not increase proportionally as the inductance (Fig. 3). There are the frequency shifts of maximal impedances towards lower frequencies, due to the presence of the parasitic capacitance of conductive layer (Fig. 6).

The frequency shift Δf is determined as the difference between the structure with the minimal number of segments ($N = 2$) and the structure with more segments (up to $N = 5$). The shift will be more pronounced if the number of segments N is greater, up to

$$\Delta f_{F19} = f(N=2) - f(N=5) = 178 \text{ MHz} \tag{4}$$

for high permeability F19 material and

$$\Delta f_{F14} = f(N=2) - f(N=5) = 0.76 \text{ GHz} \tag{5}$$

for low permeability F14 material (Fig. 6), as it was reported in [8].

Comparison of the same structure with identical geometrical parameters in F14 and F19 material shows that the device in low permeability F14 material achieves greater impedance and better suppression (up to 25 %), although it has lower inductance (up to 4 times at 1 MHz). The reason for that lies in the fact that the impedance Z is strongly determined by the resistance R (i.e. magnetic losses) in the vicinity of ferromagnetic resonant frequency, where the impedance reaches maximal value. On the other hand, high permeability material provides better suppression at lower frequencies, and devices in F19 material can be used already over 30 MHz.

Further improvement in efficiency of the ferrite EMI suppressor can be achieved by Double-coil structure ($l = 950$ µm, ϕ=40°, $w = 170$ µm, $t = 10$ µm, EIA size 1210), as it can be seen in Fig. 7. The longer conductive layer provides almost 4 times greater inductance and impedance of Double coil (L=552 nH at f=1 MHz, Z_{MAX}=295 Ω at 551 MHz) than Zig-zag (L=143 nH at f=1 MHz, Z_{MAX}=88.9 Ω at 1.6 GHz) and approximately 10 times greater inductance and impedance than Line structure 950 µm wide (L=45.1 nH at f=1 MHz, Z_{MAX}=29.1 Ω at 1.7 GHz). Again, the maximal impedance frequency shift can be noted.

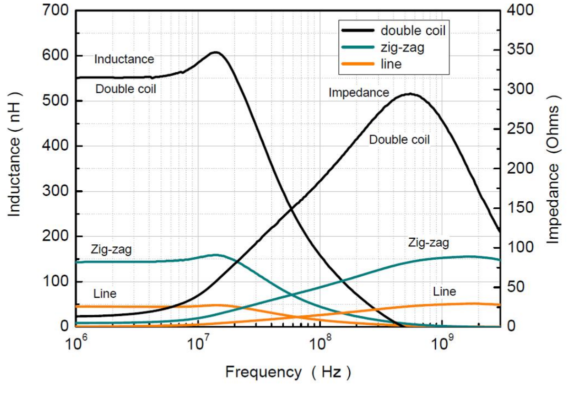


Fig. 7. The measured inductance and impedance of "Line", "Zig-zag" and "Double coil" in low permeability F14 material.

6. Conclusion

Ferrite components are not easy to model, due to the frequency-dependent and nonlinear characteristics of ferrite material. The complexity of modelling procedures rises if the component is miniaturized. An accurate description of the frequency response is achieved using a simple equivalent circuit model, which allows all parameters affecting the inductor electrical performance to be accurately predicted and controlled during the design process.

The electrical characteristics of EMI suppressor, as well as its efficiency, depend on the geometry of the conductive layer and the permeability of ferrite material, which strongly determines the possible application of ferrite component.

In order to achieve better EMI suppression, the ferrite EMI suppressor with longer conductive layer should be designed. Nevertheless, during that process, the unwanted parasitic capacitances are inevitably introduced, causing the frequency shift of the maximal impedance and a worse performance at higher frequencies. The frequency shift is more pronounced if the high permeability material is used and if the conductive layer is longer.

Comparison of the same structure with identical geometrical parameters in F14 and F19 material shows that the device in low permeability F14 material achieves greater impedance and better suppression (up to 25 %), although it has lower inductance (up to 4 times at 1 MHz). Further improvement in efficiency of ferrite EMI suppressor can be achieved by using more complex structures, like Double-coil or multilayer structures.

Acknowledgments

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