

Modeling of Ferrite Common Mode Chokes for EMI Suppression in LTCC Technology

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Abstract — In this paper, proposed structure of ferrite common mode choke for suppression of conductive electromagnetic interference (EMI) will be presented. The proposed chokes can be realized in low temperature co-fired ceramics (LTCC) technology. LTCC technology is chosen in order to achieve better performance passive components, with excellent thermal and high frequency electrical performance. Proposed choke consists of two highly conductive multilayer quadratic spiral type inductors, embedded in ferrite material 40012. To obtain the optimal design of choke, the simulation tool ILCMC for calculation of insertion loss of common mode choke is used. Simulations have been conducted for different geometrical dimensions of structure of the common mode choke using software tool ILCMC. Insertion losses of proposed components are calculated and compared.

Index Terms — Electromagnetic interference, ferrite devices, loss, modeling, simulation software.

I. INTRODUCTION

Common mode chokes are widely used in modern electronic equipment for suppression or reduction of electromagnetic interference (EMI). The size, performance and reliability make common mode chokes very attractive for a wide range of applications, especially in modern telecommunications systems, high-speed data and signal lines. This paper presents proposed structure of ferrite common mode choke in low temperature co-fired ceramics (LTCC) technology for suppression of conductive EMI. The LTCC technology is chosen for its many advantages: low cost due to parallel execution of several steps in the production process (in contrast to conventional thick technology), a possibility of massive automated manufacturing, relatively simple and inexpensive fabrication techniques, and more importantly, a great opportunity for design and production of 3-dimensional circuits [1]. Known for its excellent thermal and high frequency electrical performance, LTCC technology is gaining new applications e.g. in the automotive and telecommunications market [2].

Different shapes of common mode chokes have been proposed during past years. The characteristics of coil that consists of ferrite core, bobbin and wire are presented in [3]. This component has been developed as EMI countermeasure for ISDN, ADSL and 10Base-T telecommunications ports. Similarly, ferrite bead arrays provide good attenuation across a wide frequency range for general and high speed signal lines [4]. They consist of inner electrodes in the ferrite structure.

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Currently the need for size reduction is being addressed with small wire wound toroidal cores. They have advantage over conventional wound components regarding their low total weight, outstanding reproducibility of electrical parameters, excellent thermal performance and high degree of integration [5], [6]. Nevertheless, the fact that fabrication by automated means is precluded, because of their size and shape, has a negative impact on their cost [7].

In order to achieve better performance passive components, the possibility of their production in LTCC is discussed in [8] – [10]. In this scheme, wire winding is not required. The current carrying inductive elements and connecting conductors are screen-printed on ferrite sheets, which are stacked and formed into a monolithic body. Size reduction is achieved since the inductors are buried in a magnetic matrix, while the low cost requirement is realized via the parallel processing methods associated with LTCC.

II. EMI SOURCES AND PROPAGATION

Interference can propagate as an electromagnetic wave in free space, but also as a current via conductive paths such as the mains network, to which the majority of electrical equipment is connected. Common mode noise occurs simultaneously on both lines of a conductor pair with respect to a common ground, mainly at high frequencies, from approximately 1 MHz upwards (Fig. 1) Below 30 MHz, this is the main propagation mode. Effective suppression is achieved by placing high impedance in series (inductor), low impedance in parallel (capacitor) or a combination of both (filter) [7].

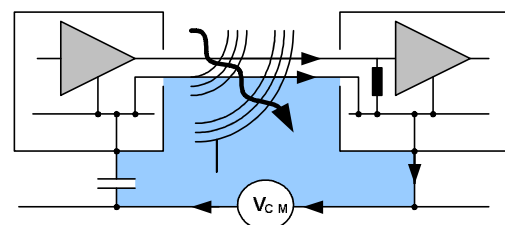


Fig. 1. Field common-mode coupling [5].

The insertion loss is a criterion for the effectivity of interference suppression components, as measured by using a standardized measurement circuit, called Line Impedance Stabilization Network (LISN), presented in Fig. 2 [11].

The input terminals of equipment under test are connected to an RF generator with impedance Z , which is usually 50Ω . At the output end of the component, the voltage is measured using a selective voltmeter having the same

impedance $Z_L = Z$.

The insertion loss A_{dB} (in dB) is calculated from the quotient of the output voltage V_{20} without filter,

$$V_{20} = V_0 \cdot (Z_L / (Z_L + Z)) = V_0 / 2 \quad (1)$$

and the output voltage V_2 with filter,

$$A_{dB} = 20 \cdot \log |V_{20} / V_2|, \quad (2)$$

where V_0 is the voltage of the signal source.

This definition of insertion loss is taking into account common mode and differential mode loss. In ideal case, the common mode choke has high impedance for common mode current and zero impedance for differential mode current.

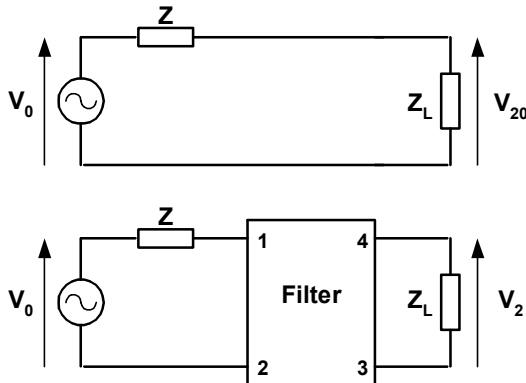


Fig. 2 Insertion loss measurement [11].

III. PROPOSED COMMON MODE CHOKE FOR EMI SUPPRESSION

Different shapes of inductive components can be manufactured in LTCC technology (in surface or buried form). The component's electrical characteristics are determined by the stack structure and ground placement. Different structures RF chokes, consisting of planar coils embedded in LTCC ferrite (between two or above one ground plane) are reported in [12].

The usual types of inductor designed in LTCC technology are meander, rectangular and round spiral, horizontal and 3-D helical type. The spiral type structure is specially good for achieving the higher inductance, and hence, the greater insertion loss and EMI suppression [13].

Proposed common mode choke consists of two highly conductive coils embedded in a ferrite monolithic structure, which provides a good magnetic shielding (Fig. 3a). It consists of two 3-D quadratic spiral type conductive layers, embedded in ferrite material. The distance between coils is t_C . Note that the coils are not one above the other, but arrange relatively by the half of the pitch p , in order to reduce capacitance between primary and secondary coil C_{12} .

Primary and secondary coils have the same geometrical parameters, in order to achieve the best symmetry between

Symbol	Font	Dimension
N	Number of turns	2, 3, 4
N_C	Number of conductive layers in primary and secondary coils	1, 2, 3, 4
w	Width of conductive layers	150 μm , 200 μm
T	Thickness of conductive layers	35 μm
t_C	Core thickness between layers	65 μm
l_{C1}	Length of outer conductive segment	3320 μm
P	Distance between centers of neighboring conductive segments	100 μm , 150 μm , 200 μm

them. Other geometrical parameters of conductive layers are presented in Table I.

Contacts of coils are 500 μm long and wide. Contacts of primary coil are denoted 1 and 4 (yellow line) and contacts of secondary coil are denoted 2 and 3 (red line). Numeration of contacts can be seen in Fig. 3a, too. Mechanical dimensions of proposed common mode chokes (Fig. 3b) are EIA standard size 1812 (3.05 mm \times 4.57 mm \times 1.6 mm).

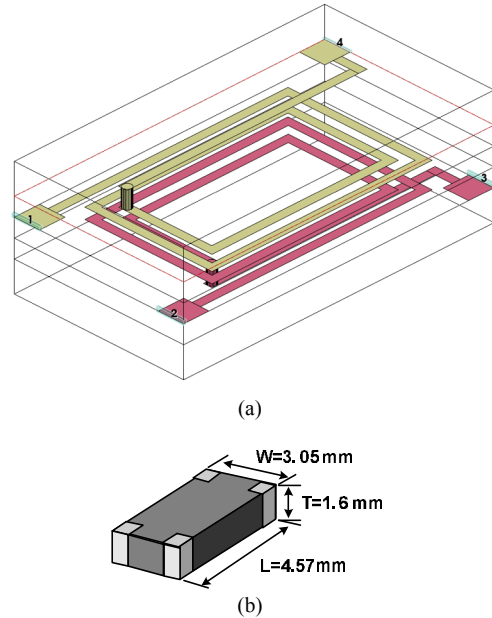


Fig. 3. (a) 3-dimensional structure of EMI common mode choke, (b) SMD component standard EIA size 1812 (3.05 mm \times 4.57 mm \times 1.6 mm).

The LTCC technology is chosen for its many advantages: relatively simple and inexpensive fabrication techniques, and more importantly, a great opportunity for design and production of 3-D circuits, like proposed structure of common mode choke should be. Besides that, the LTCC technology can be applied to fabricate other passive components, such as resistors and capacitors, and contributes to the high integration of the microelectronic circuits [1]. The LTCC 3-D design approach, where some or all of the passive components can be buried in the interior of the module, leaves room on the surface for ICs which can provide desired added functionality and increased reliability due to a reduction in the number of solder joints [14].

The LTCC systems required the development of a materials system that could be fired at low temperatures and result in dense, flat, crack-free parts. Compatible magnetic tapes, dielectric pastes, conductors and via fill pastes were needed [15].

In order to achieve greater inductances, impedance and insertion loss of magnetic component, the high permeability magnetic material has to be chosen. Therefore, we have selected NiZn ferrite material with the highest initial permeability, useful in high frequency applications, ESL 40012 [16]. For example, the same manufacturer has three ferrite materials: low permeability material 40010 has initial permeability $\mu_r \geq 60$, material 40011 has $\mu_r \geq 200$, while material 40012 has $\mu_r \geq 450$. Besides that, ferrite 40012 has high resistivity and relative ease in processing. This material is designed to be fired at 885°C to give a dense body. The thickness of magnetic tape is 65-75 μm .

Silver based materials 903-A and 902 [17] are chosen for

the conductor and via fill are chosen, because of its high conductivity and compatibility with selected ferrite tapes.

IV. MODEL OF COMMON MODE CHOKE

Common mode choke is modeled using the equivalent circuit depicted in Fig. 6, where L_1 and L_2 are inductances of primary and secondary coil, R_1 and R_2 are serial resistance of primary and secondary coil, respectively, while M is mutual inductance between coils. Primary coil capacitance is denoted C_1 , secondary coil capacitance is C_2 and C_{12} is primary to secondary coil capacitance.

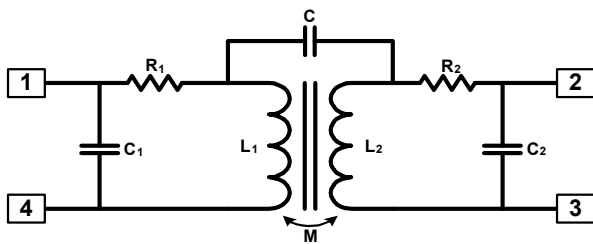


Fig. 4. Equivalent model of common mode choke [18]

Using the model of common mode choke given in [18] and the measurement circuit LISN, shown in Fig. 4, the insertion loss of common mode choke can be determined as

$$A_{dB} = 20 \cdot \log(Z_0 / [(Z_L + R_{eq} - \omega^2 C_{12} Z_L X_{eq})^2 + (X_{eq} + C_{12} Z_L R_{eq})^2]^{1/2}) \quad (3)$$

where are

$$R_{eq} = Z_0 + \frac{R_1(1 - \omega^2 C_1(L_1 + M)) + \omega^2 C_1 R_1(L_1 + M)}{(1 - \omega^2 C_1(L_1 + M))^2 + (\omega C_1 R_1)^2} + \frac{R_2(1 - \omega^2 C_2(L_2 + M)) + \omega^2 C_2 R_2(L_2 + M)}{(1 - \omega^2 C_2(L_2 + M))^2 + (\omega C_2 R_2)^2} \quad (4)$$

and

$$X_{eq} = \frac{(L_1 + M) \cdot (1 - \omega^2 C_1(L_1 + M) - C_1 R_1^2)}{(1 - \omega^2 C_1(L_1 + M))^2 + (\omega C_1 R_1)^2} + \frac{(L_2 + M) \cdot (1 - \omega^2 C_2(L_2 + M) - C_2 R_2^2)}{(1 - \omega^2 C_2(L_2 + M))^2 + (\omega C_2 R_2)^2} \quad (5)$$

Calculation of insertion loss of ferrite components for EMI suppression, including common mode chokes, is very complex since ferrite materials have non-linear characteristics. Because of that, the most of the commercially available EM simulators cannot calculate these characteristics and we have to use simulation tool that we have developed for that purpose.

Using equations (3) – (5), we have developed simulation tool for calculation of electrical characteristics and insertion loss of common mode choke. This simulation tool ILCMC (Insertion Loss of Common Mode Choke) simulates effects of ferrite materials and geometrical parameters of planar inductive structures. It uses the same principles like previously developed SPISTM (Simulator for Planar Inductive Structures), which is experimentally verified [19].

The calculation procedure is described with more details in [20].

V. RESULTS OF SIMULATIONS

The influence of common mode choke geometry on the

insertion loss is presented in this Section. The simulation results for different number of number of turn in conductive layer, and different number of layers in primary and secondary coils are presented.

As it can be seen in Fig. 5, the insertion loss of common mode choke is frequency dependent. It should be noted that the presence of ferrite material dominantly determines the non-linear shape of these curves. At low frequencies losses in choke are low. Component has dominantly inductive character and signal can pass throughout without attenuation. At higher frequencies the choke the effective suppression is achieved.

The simulation results for the different number of turns ($N = 2$, $N = 3$ and $N = 4$) in a single conductive layer $N_C = 1$ (structure depicted in Fig. 3a) shows that the insertion loss is greater if the structure has more turns. If the number of turns is bigger, inductances of primary and secondary coil and mutual inductance between coils increase. Because of that, impedance of choke and insertion loss rise.

Even more effectively insertion loss can be obtained in the structure has more conductive layers, due to increase of inductances of coils and the coupling between them. For $N_C = 2$ the insertion loss has its maximum $A_{dBmax} = 27.32$ dB at frequency 202 MHz. If the primary and secondary coils have more conductive layers, the insertion loss rises.

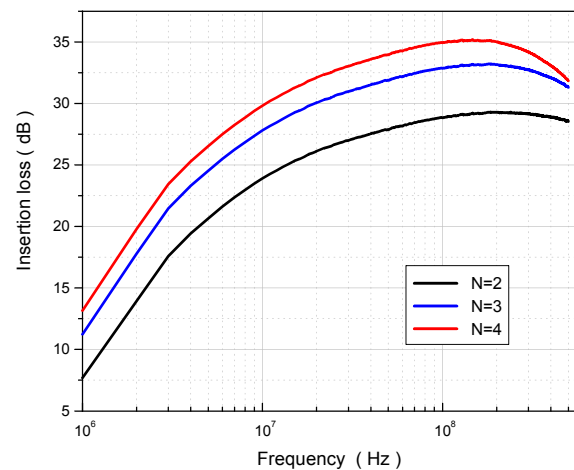


Fig. 5. Insertion loss for different number of turns in 40012 material ($w = 150 \mu\text{m}$, $p = 100 \mu\text{m}$, $t = 35 \mu\text{m}$, $t_c = 65 \mu\text{m}$, $N_C = 1$).

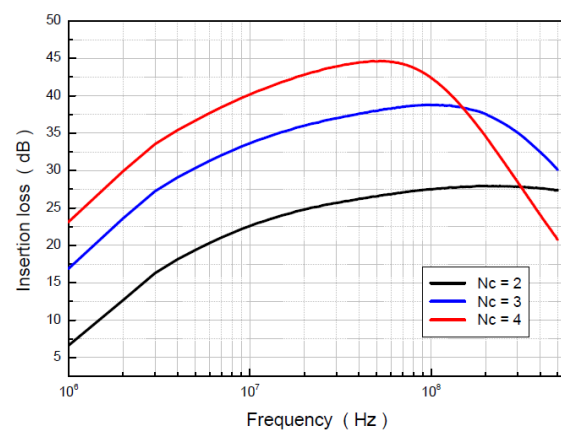


Fig. 6. Insertion loss for different number of conductive layers N_C in 40012 material ($w = 200 \mu\text{m}$, $p = 100 \mu\text{m}$, $t = 35 \mu\text{m}$, $t_c = 65 \mu\text{m}$, $N = 2$).

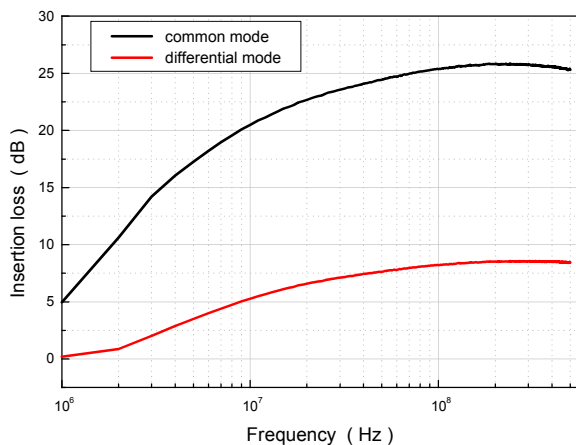


Fig. 7. Common mode and differential mode insertion loss for choke in 40012 ($w = 200 \mu\text{m}$, $p = 200 \mu\text{m}$, $t = 35 \mu\text{m}$, $t_c = 65 \mu\text{m}$, $N_c = 1$, $N = 2$).

However, it should be noted that the frequency range where the components can be used for EMI suppression is shifting towards lower frequencies (for $N_C = 3$, $\text{AdB}_{\text{max}} = 38.77\text{dB}$ at 96 MHz , and for $N_C = 4$, $\text{AdB}_{\text{max}} = 44.60 \text{ dB}$ at 50 MHz). Fig. 6 shows the insertion loss for different number of conductive layers N_C in 40012 ferrite material. Other geometrical parameters are the same for all structures ($w = 200 \mu\text{m}$, $p = 100 \mu\text{m}$, $t = 35 \mu\text{m}$, $t_c = 65 \mu\text{m}$, $N_C = 2$).

Common mode and differential mode insertion losses for common mode choke in 40012 ferrite material are shown in Fig. 7 ($w = 200 \mu\text{m}$, $p = 200 \mu\text{m}$, $t = 35 \mu\text{m}$, $t_c = 65 \mu\text{m}$, $N_C = 1$, $N = 2$). As it can be seen, the common mode insertion loss is significantly greater than differential mode, which is very good. For common mode choke it is very important to have as great as possible common mode insertion loss, while differential mode insertion loss should be kept low. In that case, signal will be kept without distortion, while unwanted interference will be suppressed.

VI. CONCLUSION

The main advantage of LTCC technology is possibility to design 3-dimensional structures. Because of that, we have chosen this technology for proposed common mode choke.

The main goal of this work is to develop a scheme for producing small, low profile passive components. Reducing the common mode choke size is required for more efficient use of space. This can be achieved by embedding two highly conductive layers into the ferrite material.

In order to achieve greater insertion loss, it is important to design structure with great inductance of primary and secondary coils, and mutual inductance between coils. Because of that, we have analyzed quadratic spirals in one or more conductive layers. Each extra conductive layer increases the insertion loss for at least 10 dB.

Nevertheless, at the same time, the unwanted parasitic capacitances are inevitably introduced, causing the frequency shift of maximal impedance and maximal insertion loss towards lower frequencies and worse performance at higher frequencies. The same frequency shift is reported in [21]. This effect should be taken into account

while designing the common mode chokes.

In order to calculate the electrical characteristics of ferrite common mode chokes in LTCC technology, we have to develop the simulation tool ILCMC. It simulates effects of ferrite materials and geometrical parameters of common mode chokes. This simulation results will be very useful for construction of the common mode choke.

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