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SPECIAL TOPIC: Advances in
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LTCC magnetic components for high density power converter

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This paper deals with multilayer magnetic components for power electronics application and specifically for high frequency switching. New formulations based on nickel-zinc-copper spinel ferrites were developed for high power and high frequency applications. These ferrites can be sintered at low temperature (around 900°C) which makes them compatible with the LTCC (Low Temperature Co-fired Ceramics) technology. Metallic parts of silver or gold can be fully integrated inside the ferrite while guaranteeing the integrity of both the ferrite and the metal. To make inductors or transformers with the required properties, it is mandatory to have nonmagnetic parts between the turns of the winding. Then it is essential to find a dielectric material, which can be co-sintered both with the ferrite and the metal. We will present the solution we found to this problem and we will describe the results we obtained for a multilayer co-sintered transformer. We will see that these new components have good performance compared with the state of the art and are very promising for developing high density switching mode power supplies. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). <https://doi.org/10.1063/1.4994252>

I. INTRODUCTION

Magnetic components integration is today a major concern in power electronics. Size reduction of inductors and transformers is mandatory to increase the power density. In consequence new low losses magnetic materials with new integration techniques are required. Furthermore the emergence of new active components based on GaN opens the way for increasing the switching frequency (several MHz) which leads to the decrease of the passive components size. At high frequency, spinel ferrites are the best low losses magnetic materials. In power electronics, these devices are conventionally built by using copper or aluminum wires wound on a ferrite core made by sintering at high temperature ($T > 1200^{\circ}\text{C}$). Planar cores with copper winding integrated in PCB allow making low profile components but the thermal behavior is still a major drawback.

In this study, we propose to make very low profile magnetic components incorporating the winding directly inside the ferrite core in order to maximize the thermal conduction.

II. LTCC COMPATIBLE FERRITES

Direct integration of windings inside ferrite cores can be achieved by using the LTCC (low Temperature Cofired Ceramics) technology.¹ For this, it is mandatory to use ferrites which can be sintered at low temperature around 900°C. Nickel-zinc-copper ferrites have a low sintering temperature and are already used to produce multilayer chip inductors. Nevertheless, their power losses are high and this is the reason why these ferrites are used for low power applications. Cobalt substitutions are very

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efficient for decreasing the power losses without modifying the sintering temperature.² Thus, these ferrites can be used to make low losses multilayer power magnetic components.^{3,4}

To make a power inductor or transformer, it is also necessary to have non-magnetic parts around the winding to avoid leakage of magnetic flux and/or to obtain the required breakdown voltage. Therefore, the ferrite must be co-sintered not only with metallic parts for the winding but also with the non-magnetic parts.

To make the non-magnetic parts, we proposed to use a ferrite similar to the NiZnCuCo ferrite but with paramagnetic properties. The goal was to facilitate the co-sintering by using two materials having similar shrinkage and thermal expansion coefficients. This was achieved by choosing a NiZnCu ferrite with high zinc content.⁵

III. FERRITE PREPARATION

In this study, we prepared nickel-zinc-copper ferrites by using the conventional ceramic route. Industrial grade raw materials (Fe_2O_3 , NiO, ZnO, CuO et Co_3O_4) were ball milled during 24 h in water and calcined at 800°C . A second milling was performed by attrition to adjust the specific area. Then the ferrite powder was tape cast by using the Doctor blade technique. Two formulations were selected for the realization of the multilayer components:

- One having magnetic properties to make the core. Its formulation was $\text{Ni}_{0.35}\text{Zn}_{0.55}\text{Cu}_{0.10}\text{Co}_{0.014}\text{Fe}_{2-\delta}\text{O}_{4-\gamma}$ and its permeability for standard pressing and sintering was around 250.
- One with paramagnetic properties to make the dielectric parts. Its formulation was $\text{Ni}_{0.05}\text{Zn}_{0.75}\text{Cu}_{0.20}\text{Fe}_{2-\delta}\text{O}_{4-\gamma}$ and its permeability for standard pressing and sintering was around 1 between -50 and $+200^\circ\text{C}$.

A small content of bismuth oxide was added to both ferrites to ensure the low sintering temperature of 900°C .

IV. FERRITE CHARACTERIZATIONS

A. Paramagnetic ferrite

The permeability was obtained by measuring the inductance of a toroid sample versus temperature. To make the toroid, several tape layers were laminated and sintered before machining. When approaching the Curie temperature, the permeability strongly decreases indicating the transition towards paramagnetic state (see figure 1).

At $T > -65^\circ\text{C}$, we observed that the ferrite had mainly a dielectric behavior. The permittivity was measured by using a capacitive method, we obtained $\epsilon' = 14$ and $\tan\delta_\epsilon < 10^{-3}$ at 1 MHz.

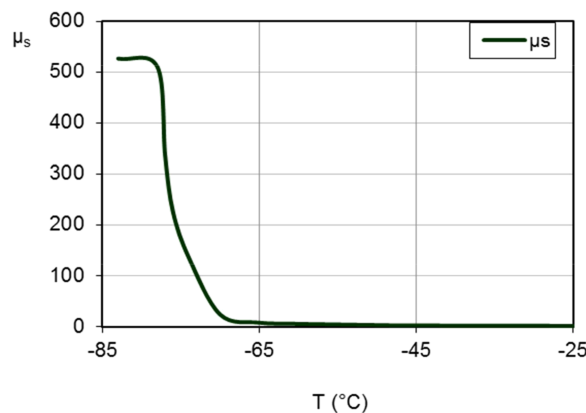


FIG. 1. Permeability of the “paramagnetic ferrite” versus temperature.

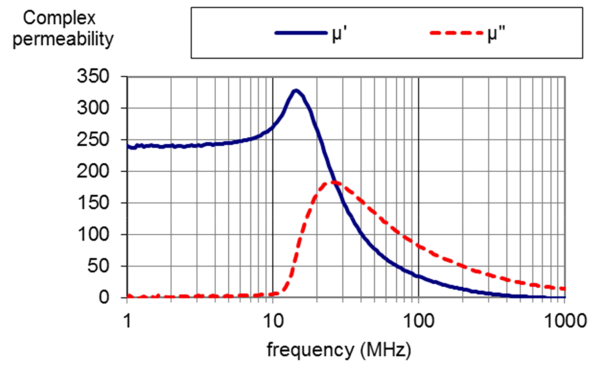


FIG. 2. Complex permeability of the “magnetic” ferrite versus frequency.

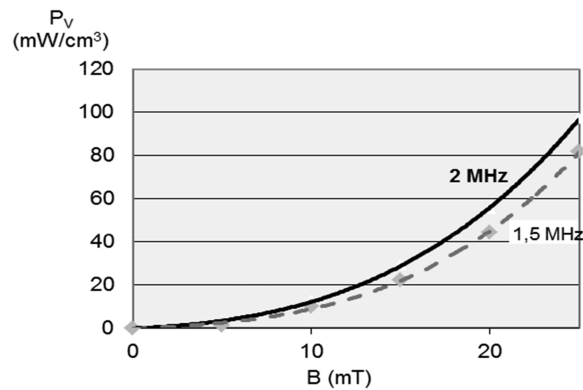


FIG. 3. Volume core losses versus induction level of the “magnetic” ferrite prepared by tape casting.

B. Magnetic ferrite

To perform the measurements on toroid samples, several tape layers were laminated and sintered before machining. First, the complex permeability was measured versus frequency. The results are given in figure 2.

We obtained a static permeability close to 250 which was measured on the bulk ferrite.

The core losses were measured on the same toroid sample. The results are given in figure 3.

We observed very low losses, lower than the ones of the bulk ferrite (around 250 mW/cm³ at 25 mT and 1.5 MHz). This was attributed to a finer microstructure as the grain size was 2 times smaller than the bulk ferrite (average grain size around 2 μm compared with 4 μm for the bulk ferrite).

V. MULTILAYER MAGNETIC COMPONENTS

Multilayer transformer was built by using the magnetic and paramagnetic ferrites. It consisted in 2 turns at the primary and 2 turns at the secondary (see figure 4).

Four layers were stacked as depicted before. On each layer, 1 turn of silver was deposited by screen-printing. Then, the turns were connected two by two as shown in figure 5. The transformer was sintered at 900°C during 2 hours in air.

The core losses were measured for each separate winding as an inductor. We obtained less than 500 mW/cm³ at 2 MHz for an input voltage of 15V.

VI. CONVERTER DEMONSTRATOR

The conversion structure for the demonstrator was a series resonance power supply.⁶ The scheme of the converter is given in figure 6. In this structure, the resonance is obtained at the primary by using

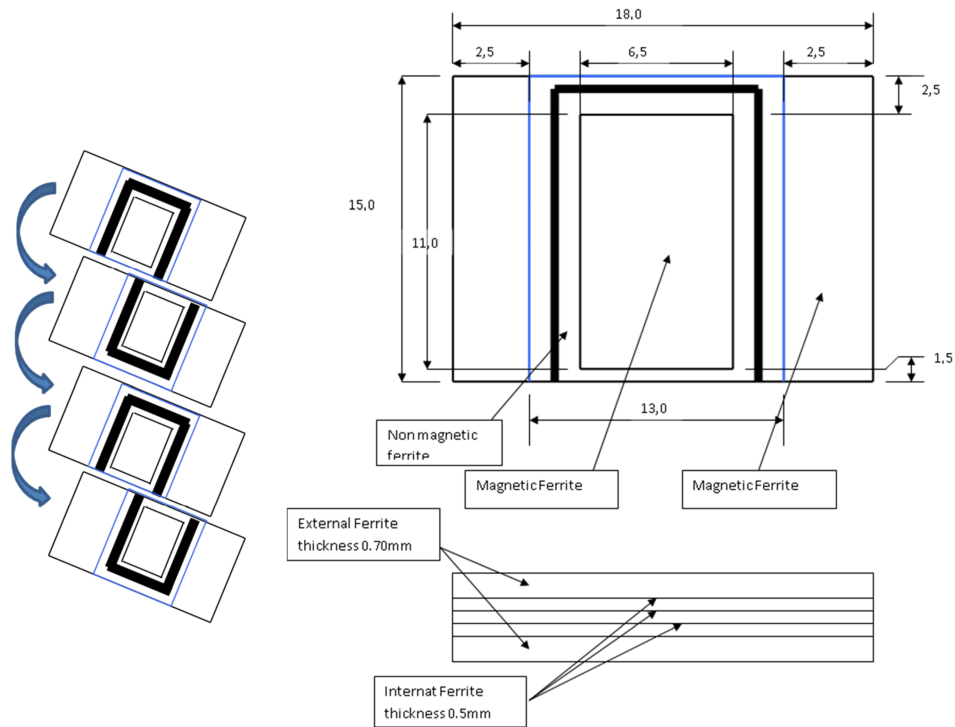


FIG. 4. Scheme of the multilayer transformer.



FIG. 5. Description of the connection of the turns.

the leakage inductance of the transformer connected with a 200 nF series capacitor. The secondary is a push-pull structure operating as a synchronous rectifier. The active components were GaN transistors (EPC9005) to ensure high frequency operating.

The transformer volume was very low allowing a strong volume reduction of the converter (see figure 7). Its characteristics are summarized in table I.

The electrical parameters of this converter are:

- Input voltage: 12 V
- Output voltage: 1.8 V
- Output current: 0.5 A

The resulting transmitted power was deliberately chosen low just to demonstrate the possible operating of such converter. We obtained an efficiency of 70% for a transmitted power of 2 W.

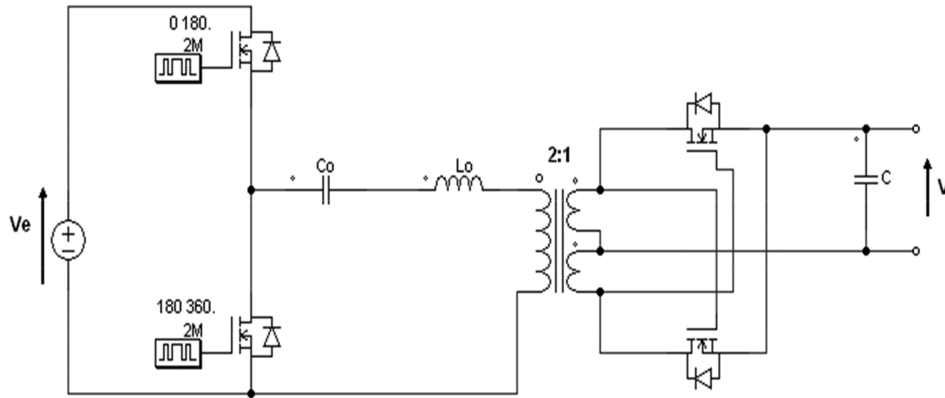


FIG. 6. Scheme of the power supply structure used for the demonstrator.

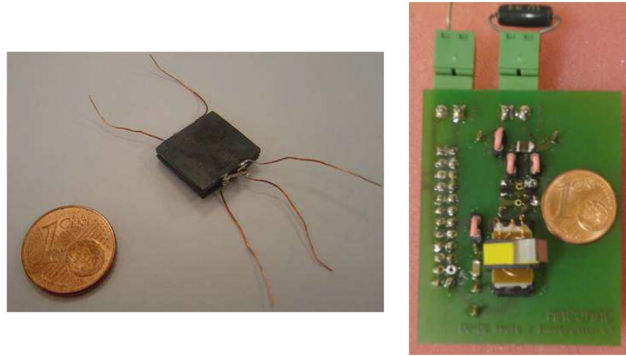


FIG. 7. photo of the transformer and the power supply.

TABLE I. Characteristics of the co-sintered transformer.

Rated voltage	2:1
Magnetizing inductance	400 nH
Leakage inductance	4.7 μ H

VII. CONCLUSION

We demonstrated the feasibility of a high frequency power converter implementing a very low size and low profile transformer. The transformer was realized by using a multilayer ceramic technology and new ferrite formulations.

The magnetic parts of the transformer were made with a low core losses and low sintering temperature NiZnCuCo ferrite. The non-magnetic parts were made with a ferrite from the same group but with a much lower Curie temperature. The non-magnetic ferrite was fully compatible with the magnetic ferrite for co-sintering.

This kind of transformer can be manufactured at large scale by using a collective process based on LTCC technology. This allows the reduction of the cost of the component and a better repeatability.

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