Design, Modeling, and Analysis of a Compact Planar Transformer

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This paper presents a new design of a planar transformer. Over the surface of a flat core, meander-type design was engraved, so that symmetrically adjusted primary and secondary coils, of the same meander-type, can fit into the engraved design. Primary and secondary coils were covered with another flat core consequently forming a compact planar transformer. Windings of primary and secondary coils are printed on both sides of PCB. Conductive stripes of a winding from upper and bottom layer are connected by vias. The transformer was analyzed when the primary and secondary coils were without a core and with a core. High frequency parameters of the transformer were obtained by finite element modeling software and Impedance Analyzer HP4194A in the frequency range from 50 kHz to 1 MHz. The transformer is intended to be used in DC-DC converters (for switching frequency up to several hundred kHz).

***Index Terms*—Compact planar transformer, finite element modeling, high frequency parameters.**

I. Introduction

CURRENT technology demands are low cost and reduction in size and weight of components. Unfortunately, transformers are the very last components to follow these trends, due to their robustness and expensiveness. However, high-efficiency switching power supplies require small, thin and mountable magnetic components.

One solution to meet these requirements for magnetic components is LTCC (*Low Temperature Co-fired Ceramics*) technology. This approach provides parallel manufacturing process which enables low cost, reduction in size and very small thickness. Some designs of LTCC ferrite transformers were reported in [1]–[3].

The other solution is planar technology. A comprehensive survey of planar magnetic techniques and technologies used for magnetic components in DC/DC converters was reported in [4]. E-cores are commonly used to wedge PCB winding or copper foil winding in a planar transformer [5]–[7].

For low-power-level application, it is possible to use coreless PCB transformers. The primary and secondary windings are etched on both sides of dielectric laminate and covered by self-adhesive ferrite polymer composite to shield the magnetic flux as it is reported in [8], [9].

The shielding effect could be improved using ferrite plates which are coated by copper sheets thus suppressing the normal component of the H-filed inside the ferrite plate [10]. A high frequency planar transformer, combination of ferrite plates and coreless transformer, is described in [11]. Strip lines of the upper layer and bottom layer of the PCB are connected by vias to form a helical loop of primary and secondary coils.

This paper discusses a new design of a compact planar transformer. Symmetrically adjusted primary and secondary coils are fit into the engraved surface of ferrite plate and covered with another ferrite plate. Such a compact design decreases the thickness of a transformer in comparison with transformers which use E-cores or transformers where two ferrite plates wedge PCB with printed windings.

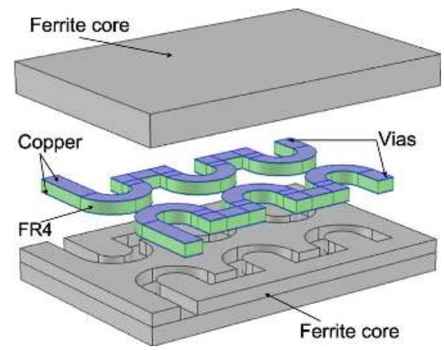

Fig. 1. The 3-dimensional structure of a compact planar transformer.

Design of the transformer is illustrated in Section II. In Section III, modeling of the transformer by *COMSOL Multiphysics* is described. Simulated and measured results of high frequency parameters of the transformer are discussed in Section IV, and conclusion follows in Section V.

II. Compact Planar Transformer Design

The 3-dimensional structure of a compact planar 1:1 transformer is presented in Fig. 1. Windings of 0.1 mm copper thickness (blue color in Fig. 1) are printed on both sides of PCB (printed circuit board—FR4 of 1.6 mm thickness, green color in Fig. 1) and mutually connected by vias, thus forming primary and secondary coils.

Geometrical parameters of symmetrical primary and secondary coils are illustrated in Fig. 2. The width of a conductor is 2.45 mm, the radius of meander arch is 4.75 mm and distance between turns is 12.75 mm.

Commercially available Ferroxcube E43/10/28 3F3 cores, with average grain size around 10 μm as it can be seen in Fig. 3, were processed so that one coil is flat and over the surface of the other coil a pattern has been engraved so that primary and secondary coils can fit into the engraved design, as it is shown

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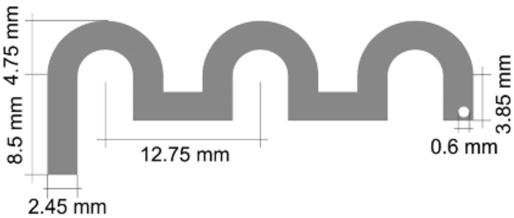

Fig. 2. Geometrical parameters of primary and secondary coils.

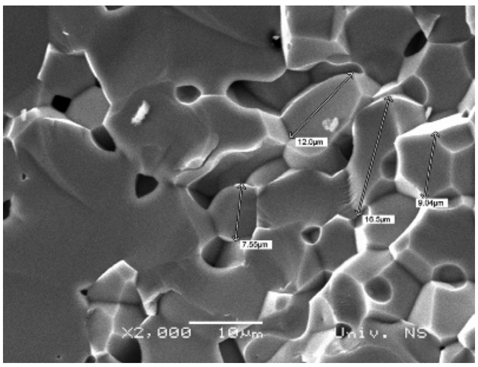

Fig. 3. The SEM micrograph of ferrite cores used for transformer's fabrication.

in Fig. 1. This particular core was used because its dimensions were suitable for achieving acceptable geometrical parameters of the transformer and reasonable processing time without breaking the core.

Due to high relative permeability of Ferroxcube 3F3 ferrite core (2000 $\pm$ 20%) the cores can go into saturation rapidly. Primary and secondary coils (number of turns and voltage across the coils), as well the effective cross sectional area of the ferrite core, are designed in an appropriate way that operational flux density is less than the value of saturation. Therefore, the ferrite core will not saturate and its operation will be almost linear for presented application.

III. Modeling of the Transformer

Finite element modeling software (*COMSOL Multiphysics*) was used to analyze magnetic flux distribution and high frequency parameters like inductance and resistance.

Because of memory and time demanding software, only one coil was analyzed due to symmetrical transformer design.

Meander coil was analyzed without a core and with a core. The relative permeability μ_r, and resistivity ρ, of the Feroxcube 3F3 ferrite core is 2000 $\pm$ 20% and 2 $\Omega\mathrm{m}$, respectively. It was taken $\mu_r = 2000$ in the simulation.

The 3D magnetic field interface, in frequency domain, is chosen, where it is assumed that

$$(j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r)A + \nabla \times H = J_e \quad (1)$$

$$B = \nabla \times A \quad (2)$$

where B denotes magnetic flux density, H magnetic field strength, J_e externally generated current density, A magnetic vector potential, σ electrical conductivity, ω the angular frequency, ε_0 vacuum permittivity, and ε_r relative permittivity.

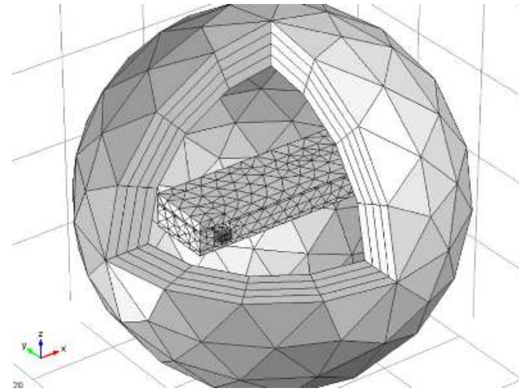

Fig. 4. Infinite elements region requires swept mesh to maintain good element quality.

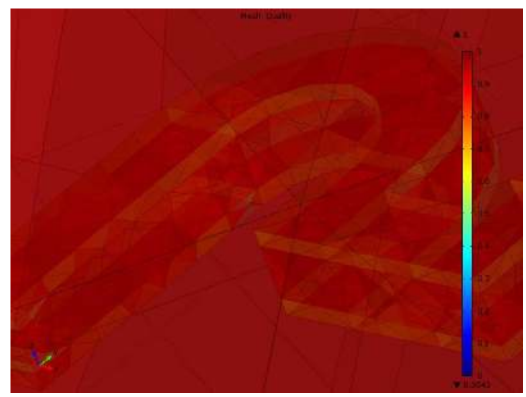

Fig. 5. Mesh quality of the model on the scale from 0 (blue color) to 1 (red color).

Air domain is a sphere, as it is shown in Fig. 4. In order to truncate geometry at the open boundaries infinite elements were used when a coil was analyzed without the core. Though, it was not necessary when the coil was analyzed with the core due to confined magnetic flux within the core.

User defined lumped port is used to excite the coil. Infinite elements region requires swept mesh to maintain good element quality, where as the remaining geometry is meshed by free tetrahedral elements, as it is shown in Fig. 4. The element size is coarse. The mesh quality of the model is illustrated in Fig. 5, on the scale from 0 (blue color) to 1 (red color).

Magnetic flux distribution is illustrated in Fig. 6 and 7. When there is no core, magnetic flux is dispersed in the air, as it is shown in Fig. 6. When the coil is enclosed by ferrite as it is described in Section II, magnetic flux is effectively confined within the core, as it is presented in Fig. 7.

IV. Discussion

High frequency parameters of the planar transformer prototype were obtained by finite element modeling software (*COMSOL Multiphysics*) and Impedance Analyzer HP4194A in the frequency range from 50 kHz to 1 MHz. A manufactured prototype of a compact planar transformer is presented in Fig. 8, where as experimental setup for its electrical characterization is shown in Fig. 9.

As for symmetrical transformer design only results for one coil are presented. Simulated values of inductance when the coil

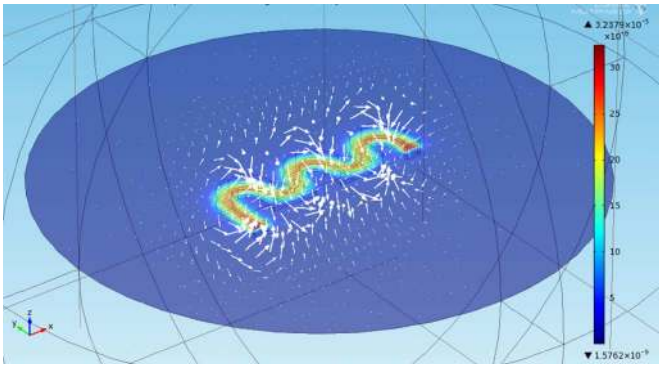

Fig. 6. Magnetic flux distribution around meander coil without the core.

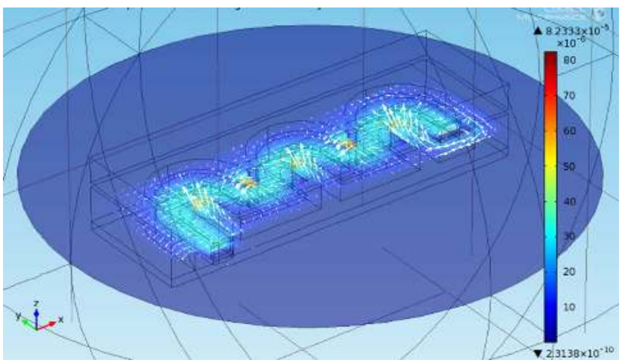

Fig. 7. Magnetic flux distribution around meander coil with the core.

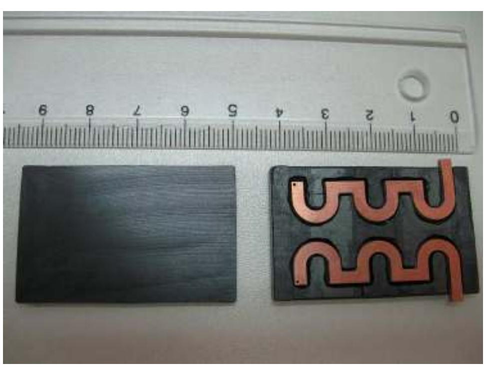

Fig. 8. A prototype of a compact planar transformer.

Fig. 9. Experimental setup for electrical characterization of the compact planar transformer.

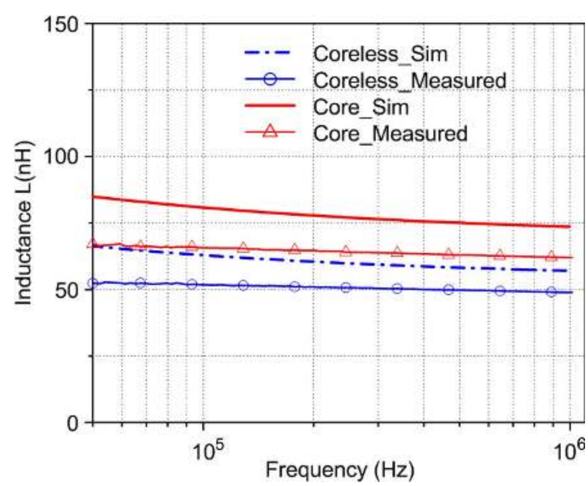

Fig. 10. Simulated and measured values of inductance when the coil is without the core and with the core.

is without the core and with the core are presented in Fig. 10. The values of inductance were obtained from post-processing as

$$L = \frac{\mathrm{Im}\{Z\}}{2\pi f}, \tag{3}$$

where $Im\{Z\}$ is imaginary part of lumped port impedance and f is frequency. At higher frequencies, the inductance is almost constant for both cases, but it is increased for approximately 15 nH when there is the core, due to high permeability of the core.

Simulated and measured values of resistance are shown in Fig. 11. These values were also obtained from post-processing as

$$R = Re\{Z\}, \tag{4}$$

where $Re\{Z\}$ is real part of the lumped port impedance. At higher frequencies the slope of the resistance increases due to skin effect in the coil.

There is discrepancy between simulated and measured results, as it could be seen in Fig. 10 and Fig. 11. There are two reasons for difference between simulated and measured values. The first reason is because of measurement set-up. The transformer's model does not take into account additional wires which were used to connect transformer to Impedance Analyzer. The second reason is air gap. The air gap is a consequence of a manufacturing process, so its dimensions are not accurately defined in advance like when a component is fabricated. Therefore, it was difficult to accurately model dimensions of the air gap.

Calculated values of coupling coefficient are presented in Fig. 12. The coupling coefficient was determined as

$$k = \frac{M}{\sqrt{L_p L_s}}, \tag{5}$$

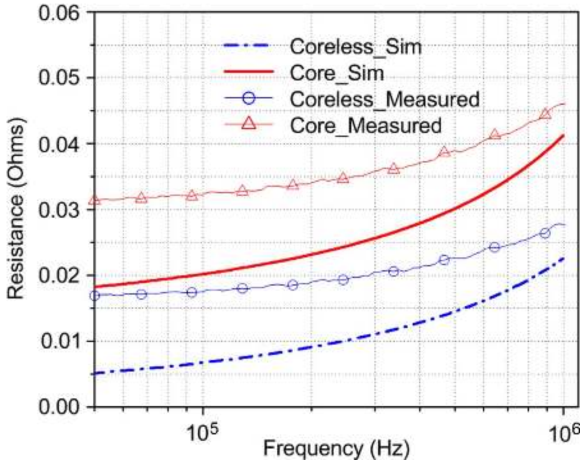

Fig. 11. Simulated and measured values of resistance when the coil is without the core and with the core.

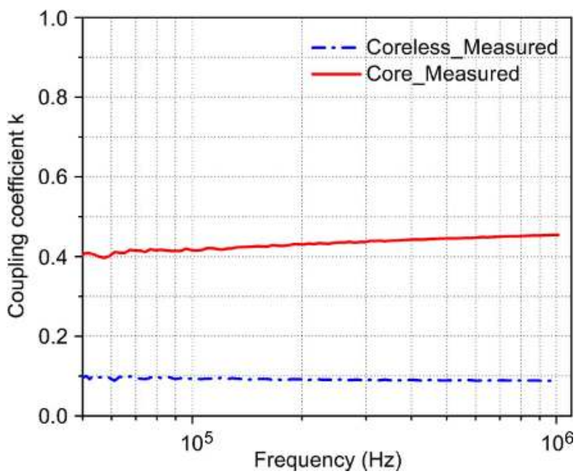

Fig. 12. Measured values of coupling coefficient when the coil is without the core and with the core.

where M is mutual inductance, L_p and L_s are measured values of inductance of the primary and secondary coil, respectively. Mutual inductance M was calculated from equation

$$L_{sc} = L_p + L_s + 2M, \tag{6}$$

where L_{sc} is the measured inductance when primary and secondary coils were connected in series, L_p and L_s are measured values of primary and secondary coils, respectively. When there is no core, coupling between primary and secondary coil is low, only 0.1. When primary and secondary coils are put into the engraved design, as it is illustrated in Fig. 1, coupling increases from 0.4 at lower frequencies to 0.5 at higher frequencies.

V. Conclusion

A compact planar transformer of a new design was analyzed in this paper. Its high frequency parameters were analyzed by finite modeling software (*COMSOL*) and Impedance Analyzer. The transformer was analyzed without the core and with the core.

Using ferritic core, the inductance was increased for 22% in comparison with coreless transformer. There is discrepancy between simulated and measured values of inductance and resistance as a consequence of measurement set-up and chosen model described in Section III.

With this compact design, coupling coefficient in medium range (around 0.5) was obtained, which is comparable with the open literature.

In future work, the focus will be on isolating primary and secondary coils from ferrite surfaces, in order to lessen the influence of air gap. The air gap is decreasing the inductance of primary and secondary coils and their coupling.

Also, the focus of future work will be on making primary and secondary coils without dielectric laminate and decreasing distance between conductive segments and their width as well, in order to increase inductance.

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