Letters

High Power Density 48–12 V DCX With 3-D PCB Winding Transformer

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***Abstract*—Planar transformer has been used in high frequency high power density dc–dc converters for its low profile. With the packaging technology development of the power devices, their footprints become smaller and smaller. However, the reduction in the core loss density of high frequency soft ferrite materials is slow, which results in an insensible reduction of the cross area of the transformer magnetic core. Hence, the transformer becomes the highest component in many high-density brick dc–dc converters, which restrict the improvement of power density. This letter proposes a three-dimensional (3-D) PCB winding structure, which surrounds the flat magnetic core. By mounting the components to the top and bottom layers of PCB windings, the transformer volume is reduced and the power density can be improved significantly. A 1.6 MHz 48–12 V 300 W DCX prototype with GaN device is built up to verify the 3-D PCB winding concept. The peak efficiency 97.3% and power density 1380 W/in^3 are achieved by using the proposed 3-D PCB winding transformer and integrated layout.**

***Index Terms*—High power density, integrated layout, MHz DCX, series resonant converter, three-dimensional (3-D) PCB winding transformer.**

I. Introduction

INTERMEDIATE bus architecture is wildly used in power supply system of telecom systems and data centers, where 48 or 380 V dc bus has been the trend for its high efficiency [1]–[4]. The 48 V dc system is considered to have higher reliability and has already been used by Google and Facebook. Because the 48 V bus voltage cannot be used directly by CPUs/GPUs, a popular solution is to step down 48–12 V first by using an isolated unregulated dc–dc converter [3]. In order to shorten the power distribution path and reduce the large bus-bar loss, the 48–12 V dc–dc converter is placed directly on the motherboard, which demands higher efficiency and higher power density dc–dc module. In order to achieve high density and high efficiency, the series resonant topologies are popular because of their soft-switching characteristic in megahertz dc–dc conversions [3]–[9]. In such high-density dc–dc converters, the planar transformers with PCB windings are adopted for their low-profile characteristic and high efficiency [10], [11]. With the series resonant topology and planar PCB winding transformer shown in Fig. 1, the power density can be improved to 900 W/in^3 [3]. Generally, for a 12 V output high current DCX converter, one turn center-tapped secondary winding is preferred due to its simple structure and high efficiency. However, for a MHz level resonant converter, the 12 V/turn of the planar transformer still leads to a large cross area of the magnetic core, which is higher than 30 mm^2, because the loss density of ferrite material increases with the increase of switching frequency. For example, when the switching frequency is 1.6 MHz, the thickness of the core (d_{core}) shown in Fig. 1(b) is around 3 mm, which is far higher than that of the devices. Therefore, the shadow area in Fig. 1(b) is wasted.

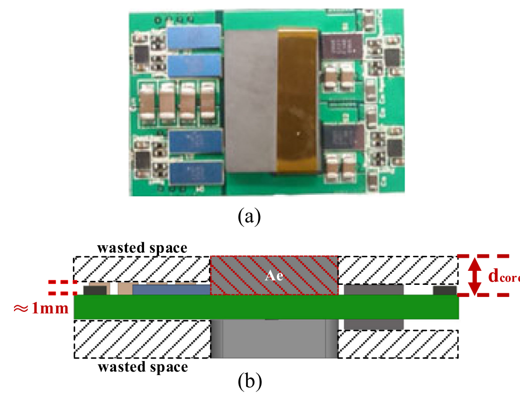

Fig. 1. Conventional planar PCB 48–12 V DCX [3]. (a) Top view of the prototype. (b) Side view diagram.

Another way of improving the power density is to embed the magnetic components into PCBs [12]–[15]. The thickness of the core determines the thickness of the whole embedded PCBs. However, for 12 V output and high output current applications, usually the secondary winding is designed to be one turn to reduce the conduction loss. Hence, the large thickness of the magnetic core brings large via losses.

Therefore, this letter analyzes the density limitation of the structure of planar transformer and proposes a three-dimensional (3-D) PCB winding structure for the transformer to lower the whole size of the converter.

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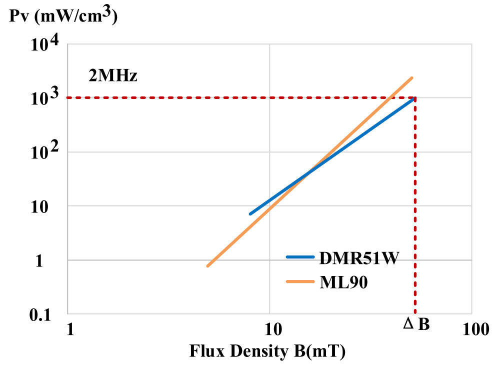

Fig. 2. Loss density characteristic of magnetic materials@100 °C.

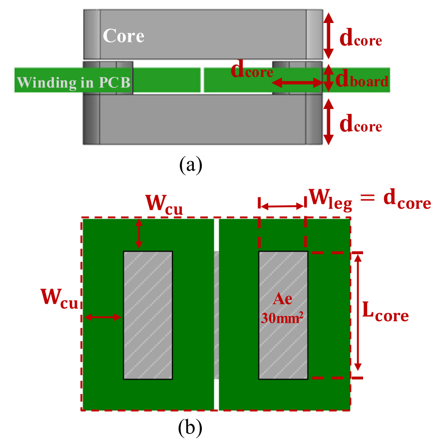

Fig. 3. Planar transformer using UI core. (a) Cross section of the transformer. (b) Structure of the windings.

II. Power Density Limitation of Planar Transformer

Due to the high loss density (P_v) of magnetic materials at MHz frequency shown in Fig. 2, the maximum flux density (ΔB) is restricted in order to keep the loss density at an expected level at different switching frequencies. Thus, for the series resonant converter, the tolerable P_v is chosen first and then the equivalent flux area can be calculated by (1)

$$A_e = \frac{D \cdot V_T}{2 \cdot N \cdot f_s \cdot \Delta B} \tag{1}$$

where D is the switches duty cycle, V_T is the secondary voltage of the transformer, N is the turn number of the secondary windings, f_s is the switching frequency, ΔB is the peak flux density, which is corresponding to P_v at given frequency. For the consideration of high efficiency and heat dissipation, P_v cannot be too high. Thus, the peak flux density (ΔB) is selected where P_v is around 1000 mW/cm^3, which is suitable for the high frequency magnetic material, DMR51W. Then, the cross area (A_e) 30 mm^2 is selected according to (1) for a 12 V output at higher than 1 MHz switching frequency, where the turn counts N equals one.

In order to get the limitation of the volume of the planar transformer, the UI core has been used in low output voltage high current dc–dc applications to construct planar matrix transformer in Fig. 3 [6]–[9], which has achieved high efficiency and high power density.

The cross section of the transformer is shown in Fig. 3(a), where d_{core} is the thickness the core. The d_{core} is higher than d_{board}, which is the thickness of the PCB. The height of the transformer (H_{tr}) can be calculated by (2)

$$H_{\text{tr}} = 2d_{\text{core}} + d_{\text{board}}. \tag{2}$$

Fig. 3(b) shows the winding structure, where W_{cu} is the width of the windings, W_{leg} is the width of the core leg, which is equal to d_{core}, L_{core} is the length of the core. For that the equivalent flux area (Ae) is fixed at 30 mm^2 as mentioned above, the length of the core can be calculated by (3)

$$L_{\text{core}} = \frac{Ae}{d_{\text{core}}}. \tag{3}$$

In order to keep the copper loss almost the same, the width of the windings (W_{cu}) will be changed as the winding perimeter changes. Using the eddy current model in [4] and [16], when the winding arrangement is well interleaved and not changed, the ac resistance coefficient is influenced by the switching frequency (f_s) and the copper thickness (d_{cu}). For the design in this letter, f_s is selected at 1.6 MHz and d_{cu} is selected at 2 oz according to f_s. Thus, the ac resistance coefficient hardly changes with the winding width (W_{cu}). To simplify the mathematical model, dc resistance of one turn of the windings (R_{dc}) is used instead. Thus, W_{cu} can be calculated in (4) once the core thickness (d_{core}) is determined

$$W_{\text{cu}} = \frac{2\rho}{d_{\text{cu}} R_{\text{dc}} - 4\rho}\left(d_{\text{core}} + \frac{\text{Ae}}{d_{\text{core}}}\right) \tag{4}$$

where ρ is the copper resistivity, d_{cu} is the thickness of the copper. Then, the volume of the whole transformer (V_{Tr}) can be calculated by (5)

$$V_{\text{Tr}}\left(d_{\text{core}}, R_{\text{dc}}\right) = \left(2W_{\text{leg}} + 4W_{\text{cu}}\right)\left(L_{\text{core}} + 2W_{\text{cu}}\right) H_{\text{tr}}. \tag{5}$$

By substituting (2), (3), (4) into (5) and assuming the thickness of the 12-layer PCB (d_{board}) to be 2 mm, V_{Tr} is

$$V_{\text{Tr}}\left(d_{\text{core}}, R_{\text{dc}}\right) = 2\left[M_e\left(d_{\text{core}}^2 + \frac{Ae^2}{d_{\text{core}}^2}\right) + N_e\right] \times \left(2d_{\text{core}} + d_{\text{board}}\right) \tag{6}$$

where $M_e = 2\alpha(2\alpha+1)$, $N_e = Ae[(2\alpha+1)^2 + (2\alpha)^2]$ and $\alpha = \frac{2\rho}{d_{\text{cu}} \cdot R\text{dc} - 4\rho}$.

According to (6), the relationship between the volume of the transformer and the d_{core} at different R_{dc} is plotted in Fig. 4. It is observed that the minimum volume can be achieved when the thickness of the core (d_{core}) is around 3.5 mm at different R_{dc}. And, the volume of the transformer will increase rapidly as d_{core} reduces below 2 mm, which means that the power density of the transformer reduces.

From the analysis in above paragraphs, the density of the planar PCB transformer is limited by its planar PCB structure.

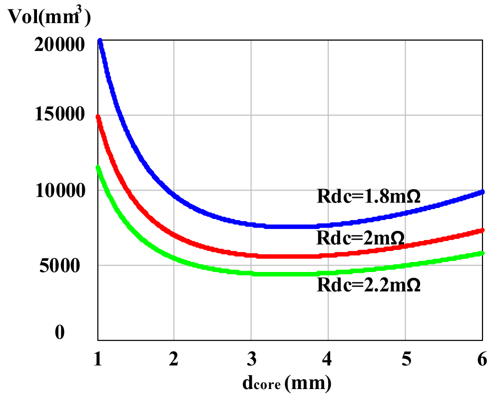

Fig. 4. V_{Tr} in function of d_{core} and R_{dc} @ 48–12 V (conventional planar transformer).

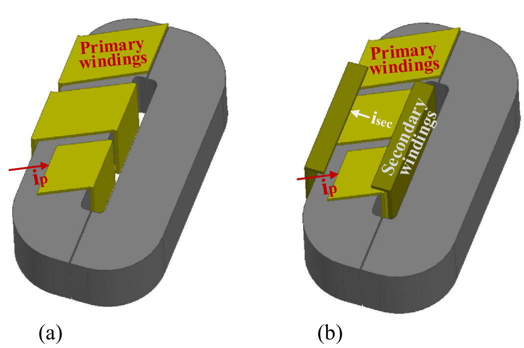

Fig. 5. Concept of 3-D PCB winding transformer. (a) Primary windings. (b) Secondary windings.

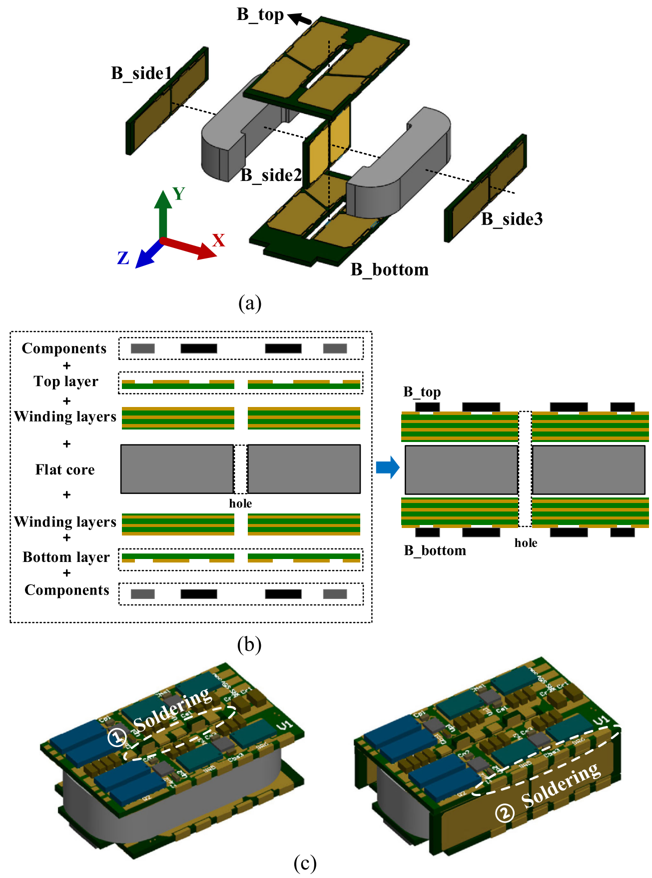

Fig. 6. Structure of the transformer (six layers). (a) Explosion diagram of the 3-D PCB winding transformer. (b) Diagram of the top and bottom PCBs. (c) Assembling steps.

III. Proposed 3-D PCB Winding Transformer

A. Structure of the 3-D PCB Winding Transformer

With windings surrounding the magnetic core shown in Fig. 5, the limitation between the volume and the cross area of the core can be eliminated. In order to construct the transformer with winding surrounding the magnetic core, PCB is still used for its good repeatability and ease of manufacturability. As shown in Fig. 6(a), five pieces of multilayer PCBs are connected by metallization processed edgings to form the windings. The decomposition diagrams of the top board (B_top) and the bottom board (B_bottom) are shown in Fig. 6(b). The top layer and the bottom layer of the PCB can be used to layout the pads and traces. Hence, all of the components can be mounted on the PCB directly. Then, the B_top and B_bottom can be connected first using $B\_\mathrm{side}\,2$. In this step, the core is assembled and the air gap can be adjusted. Finally, the $B\_\mathrm{side}\,1$ and $B\_\mathrm{side}\,3$ are soldered on the converter, as shown in Fig. 6(c). In this way, the contradiction of the core thickness and components thickness is solved. The space of the whole converter is used efficiently.

B. Power Density Improvement With the Proposed 3-D PCB Winding Structure

The size of the proposed transformer is re-evaluated as shown in Fig. 7. The racetrack flat magnetic core consists of two parts,

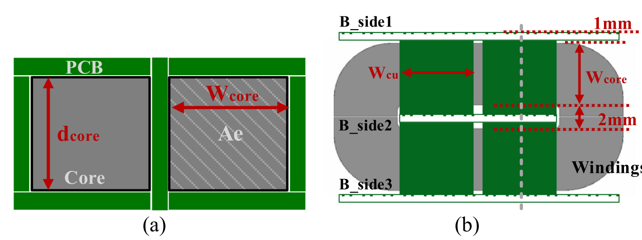

Fig. 7. Geometry structure of the proposed transformer. (a) Cross section of the proposed transformer. (b) Footprint.

which can be regarded as two legs. For each leg, there are two parallel turns of secondary windings as shown in Fig. 7(b).

The cross area (Ae) of the magnetic core is selected at 30 mm^2. Then, the height of the transformer (H_{tr}) and the width of the core cross section (W_{core}) will be determined by the thickness of the core (d_{core})

$$H_{\mathrm{tr}} = d_{\mathrm{core}} + 2d'_{\mathrm{board}}, \quad W_{\mathrm{core}} = \frac{\mathrm{Ae}}{d_{\mathrm{core}}}. \tag{7}$$

The footprint is shown in Fig. 7(b), the winding arrangement of the proposed transformer can also be well interleaved. With the same switching frequency and the same copper thickness (2 oz), the ac resistance coefficient of the proposed structure

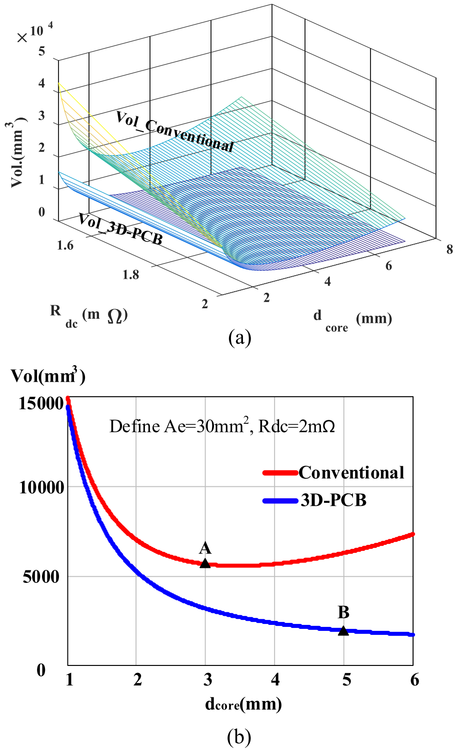

Fig. 8. Volume comparisons between planar transformer and the proposed 3-D PCB winding transformer. (a) Volume at different $d_{\rm core}$ and different $R_{\rm dc}$. (b) Volume at different $d_{\rm core}$ when $R_{\rm dc} = 2$ mΩ.

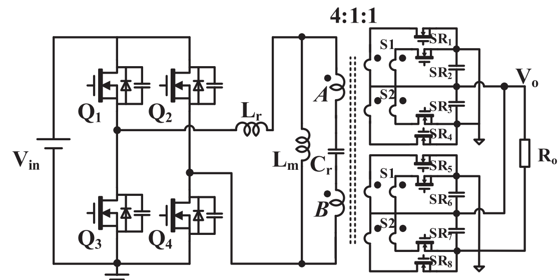

Fig. 9. Circuit diagram of the series resonant converter.

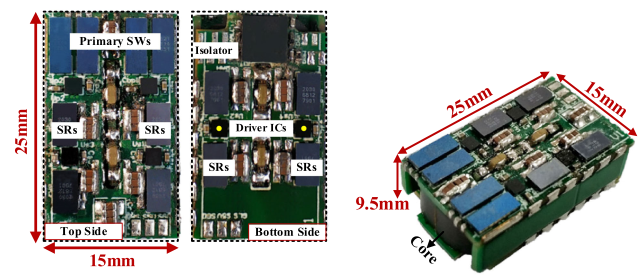

Fig. 10. Photo of the proposed 3-D PCB DCX prototype.

is around 2, simulated using finite-element method, which is similar to that of the conventional planar structure. Thus, $R_{\rm dc}$ is still used and kept the same for simplification. Thus, the winding width $(W_{\rm cu})$ will be calculated by (8)

$$W_{\rm cu} = \frac{2\rho}{d_{\rm cu}R_{\rm dc}}\left(d_{\rm core} + \frac{Ae}{d_{\rm core}}\right). \tag{8}$$

As shown in Fig. 7(b), there are two boards (*B_side1 and B_side3*) on both sides of the transformer and one board (*B_side2*) in the middle. By using the six-layer board, the thickness of the PCB $(d'_{\rm board})$ is around 1 mm. And a hole with a width of 2 mm $(d_{\rm hole})$ is reserved in the middle of the core. Then, the volume of the proposed transformer is

$$V'_{\rm tr}(d_{\rm core}, R_{\rm dc}) = \left[(4\alpha + 4)\frac{Ae^2}{d_{\rm core}^2} + (2M\alpha + 2M)\frac{Ae}{d_{\rm core}} + 2M\alpha d_{\rm core} + 4\alpha Ae\right](d_{\rm core} + 2d'_{\rm board}) \tag{9}$$

where $\alpha = \frac{2\rho}{d_{\rm cu}R_{\rm dc}}$, $M = 2d'_{\rm board} + d_{\rm hole}$.

According to (6) and (9), the volumes of the two transformers can be plotted in the same frame of axes. Then, the proposed 3-D PCB winding transformer can be compared with the conventional planar transformer mentioned in Section II in Fig. 8. It is observed that by using the 3-D PCB winding structure, the minimum volume of the transformer at the same $R_{\rm dc}$ can be reduced a lot. And, the volume of the planar transformer will increase significantly when $R_{\rm dc}$ reduces from 2 to 1.5 mΩ. By compromising between the copper loss and the power density, the $R_{\rm dc}$ is selected as 2 mΩ, as shown in Fig. 8(b). As for the planar transformer with UI core, the minimum volume is obtained at point A, where the thickness of the core $(d_{\rm core})$ is around 3 mm. When using a 12-layer PCB, the height of the planar transformer $(H_{\rm tr})$ is around 8 mm. Similarly, the core thickness for the proposed transformer can be selected around point B. Although the core thickness $(d_{\rm core})$ of the proposed transformer is larger, by (7), the height of the transformer $(H_{\rm tr})$ is calculated to be around 7 mm, which is close to that of the UI transformer. With the same dc resistance of the windings $(R_{\rm dc})$ and the same equivalent flux area (Ae), the volume of the transformer is reduced a lot. Finally, for the proposed 3-D PCB winding transformer, the thickness of the core is chosen to be 5.5 mm, where the actually designed transformer volume is around 2810 mm^3, which is reduced by 50% compared to that of the planar transformer at point A.

Finally, the circuit diagram of the 48–12 V series resonant DCX is shown in Fig. 9. By using the idea of matrix transformer [3]–[9], the single 4:1:1 transformer can be divided into two parts (2:1:1), A and B. The primary windings are connected in series while the secondary windings are connected in parallel. The leakage inductance and the magnetizing inductance are assumed as L_r and L_m, respectively.

IV. Experimental Verifications

Based on the concept of the proposed 3-D PCB winding transformer, a 1.6 MHz 48–12 V DCX prototype with rated 300 W output power is built. The prototype is shown in Fig. 10. The key parameters of the prototype are shown in Table I. The magnetic core is surrounded by the multilayer printed circuit

TABLE I
KEY PARAMETERS OF THE PROTOTYPE

Component	parameters
$Q_1 - Q_4$	EPC2021
$SR_1 - SR_8$	EPC2030
C_r/L_r	460 nF/12 nH
L_m	2.5 uH
PCB	6 Layer/2 oz
Core/Ratio	DMR51W/4:1:1

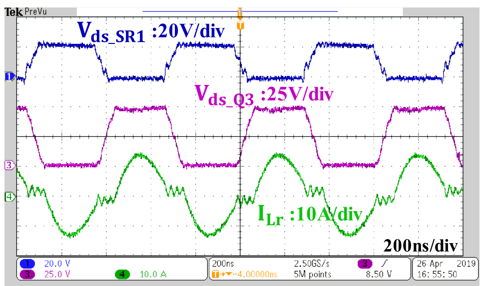

Fig. 11. Measured waveforms @ $V_{\text{in}} = 48$ V, $I_o = 25$ A.

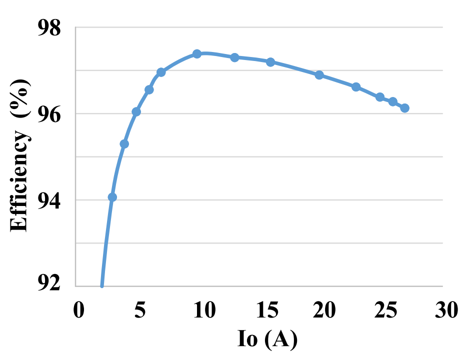

Fig. 12. Measured efficiency of the prototype.

boards; and the different boards are connected by solders. All of the components are mounted on the top and bottom layers of multilayer PCB.

The key waveforms of the prototype at 25 A output and 48 V input are shown in Fig. 11. The converter can achieve ZVS with dead time of 75 ns. The measured efficiencies of the prototype are plotted in Fig. 12; and the peak efficiency of the prototype is 97.3%. The power density of the prototype achieves 1380 W/in^3.

V. CONCLUSION

In this letter, the concept of the 3-D PCB winding transformer is proposed, and the construction principle of the PCB parallel integrated transformer is presented. The magnetic core for the 3-D PCB winding structure is designed to be flat, which is surrounded by parallel PCBs. And all of the components can be mounted on the top and bottom layers of PCB without being spread out. By properly designing the thickness of the core, the volume of the transformer can be reduced significantly and the power density of the whole dc–dc converter is improved to be much higher than 1 kW/in^3.

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