PCB embedding of Magnetic Material for Inductor-based Applications

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Abstract

During development of new generation power supplies, embedded inductors and transformers based on the embedding technology turned out to be a major step towards further miniaturization of voltage regulation modules (VRM). While the magnetic core material is integrated into the PCB by using the ECP® technology for embedding components into a printed circuit board (PCB), the copper structure is used to for the windings. After production of a first inductor build, the development was extended to additional applications for shielding magnetic fields within a PCB. Especially for small and flat packages, the technology offers advantages as the top surface can be used for surface mounted components while the bottom surface acts as mechanical and electrical connection to a motherboard.

Key words

Embedding, magnetic inlay, power electronics, miniaturization, toroid core, solenoid, ECP®

I. Introduction

Power supplies for modern electronics often use switched mode power supplies. Depending on the target application, this can be an isolated or a non-isolated version. Common for both versions is that an inductor stores energy. Usually this is one of the bulkiest components in a power delivery network. Especially when it comes to high miniaturization factors, a standard solution is too large. One available solution is a concept based on planar inductors. This approach helps to reduce the overall inductor height and supports the miniaturization of the converter in x, y and z-direction. Solutions already available on the market use the copper structure to form windings within the printed circuit board (PCB), while a ferrite encloses them and finalizes the inductor. Beside mechanical challenges, a precise definition of the air gap can become critical too. A combination of the boards copper structure, forming the windings and a magnetic material inlay inside the PCB solves all mechanical disadvantages. Additionally, all necessary air gaps can be formed precisely by PCB manufacturing equipment.

II. Scope of this work

Forming magnetic elements (e.g. inductors) by printed paste materials and the copper structure in PCBs is known since years. One drawback is the manufacturing and the in-accurate results because of printed magnetic paste materials. Also the permeability is low, so it is not possible to gain higher inductance values needed for power conversion. The scope within this paper is to show that a wiring board can contain parts like inductors, transformers or shielding structures depending on the need of the product. Due to several material combinations, the performance is optimized to the application.

III. Theoretical Explanation

A. Core shapes

Based on the application used, the optimized core shape should be selected. For a standard inductor often a solenoid shape is sufficient even with a decreased inductance value and a low EMI performance. Fig. 1 shows a comparison of the most common possible core shapes.

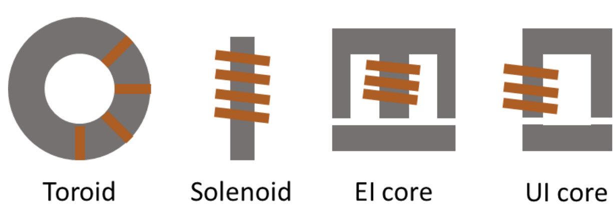

Figure 1: Most common core shapes

Toroidal core shapes are feasible for EMI sensitive applications and transformers too. The same will be true for EI/UI shapes. Every construction smaller than 20 x 20 mm and thinner than 500 µm can be used to form an inductor within a PCB now. Development also shows that constructions with two embedded magnetic sheets help to increase the inductance values.

B. Mathematical considerations

The first assumption is based on the calculation of the toroidal core shapes, while the following formula is valid for all core shapes:

$$L = \frac{N^2 \times \mu_0 \times \mu_R \times A}{l_m} \quad (1)$$

Eq. 1 takes an equal field distribution over the core area, which results in inaccurate calculation results. Additionally, in case one or more air gaps are introduced in the core, some extra losses will be caused by the fringing effect of the magnetic field lines. Fig. 2 shows the difference between no air gap, a small gap and a larger one.

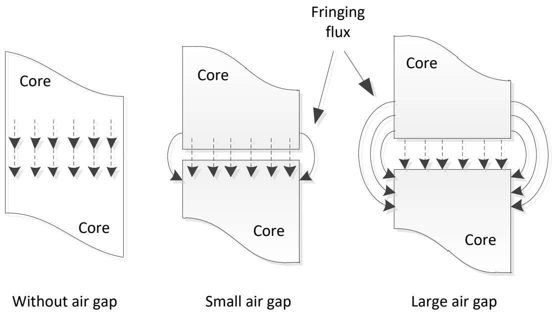

Figure 2: Distribution of magnetic field lines

Calculation of the inductance values for all demonstrators is based on formulas from literature in [1].

IV. Experimental Setup

A. Concept and Development

The demonstrator module of the planar inductor is a two-layer construction with magnetic material based on flakes to reduce the effect of the eddy currents. This material is embedded like an inlay inside the core of a PCB. Fig. 3 show the stack-up of the construction. Magnetic material (blue) is located in the center, while the toroidal winding is located around. The top and bottom copper layer is connected by plated mechanically drilled vias. The copper height used for the windings is 35 µm for all demonstrators shown. Increased copper results in decreased DC resistance and lower power loss. Future demonstrators will have increased copper heights.

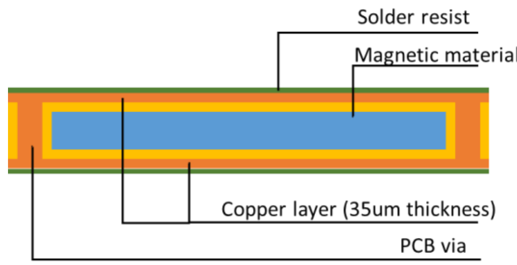

Figure 3: Inductor demonstrator build-up

Inlay installation inside the PCB uses the AT&S ECP® process. Assembly machines install the precut inlay, which behaves like a mechanical component without being electrically connected. Fig. 4 shows the process flow needed to install the part.

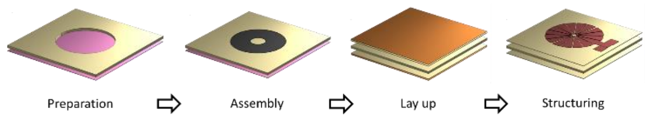

Figure 4: Inlay installation process

As depicted, a drilled hole in the core material forms the cavity necessary for the installation of the inlay. Before assembly, an adhesive tape is attached to keep the component in position before fixing it by a lamination step with prepreg material. It also fills up the cavity and encloses the inlay fully. After removal of the tape, a second lay-up step finalizes the embedding process. Drilling, plating and structuring are standard manufacturing processes. Application of a solder mask completes the PCB manufacturing process (not shown in Fig. 4). This process was used for all demonstrators presented in section IV.

V. Proof of concept

A. General

As mentioned, the technology can be used to form magnetic components. During this project, several different inductors as well as a transformer demonstrate the correct behavior. Initial reliability tests (thermal cycling tests) show that the material combination behaves as required. In the next sections, three different prototypes are described in more detail.

B. Standard inductor

The overall thickness of the construction (including the solder mask) is set to be 500 µm with a tolerance of ± 10%, while the magnetic material has a total height of 300 µm. Outer diameter of the embedded magnetic material is set to be 10.5 mm, while the diameter of the inner hole is 3 mm. As the windings enclose the flake material ring, the overall outer diameter of the coil is 12.5 mm. To simplify the connection to the measurement instrument, both pads are located at the edge of the board. Fig. 5 shows a picture of an inductor demonstrator:

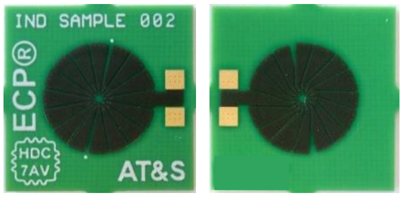

Figure 5: Demonstrator picture (top/bottom view)

A large air gap results in a high fringing of the magnetic field, which causes additional core losses. This prototype has a 150 µm small prepreg-filled air gap every 120° to ensure an equal distribution while lowering fringing effects. The following x-ray picture shows the copper structure around the dark gray magnetic material inlays. The air-gaps are indicated in red.

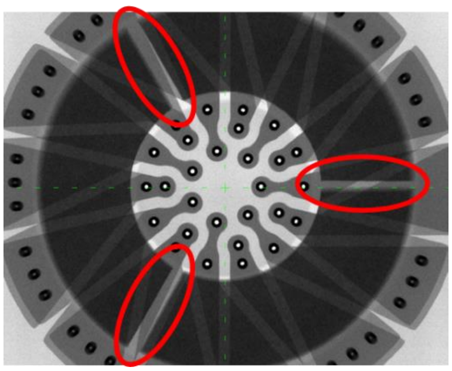

Figure 6: X-Ray of the inductor demonstrator

A simulation in CST Studio shows the performance before production. Additionally a measurement performed by a project partner describes the **L vs. I** behavior as shown in Fig. 7.

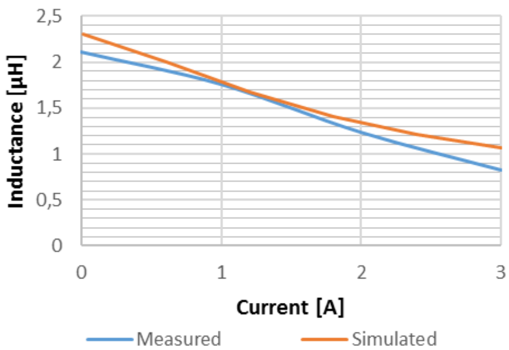

Figure 7: Evaluation results for 3 air gap version

The deviation between simulation and measurement is less than 10% in an acceptable range.

C. Wireless charging unit

A demonstrator based on a Qi-compliant charging controller from NXP shows that material inlays can shield magnetic field lines and straighten a field into a certain direction. The following principle block diagram shows the functionality.

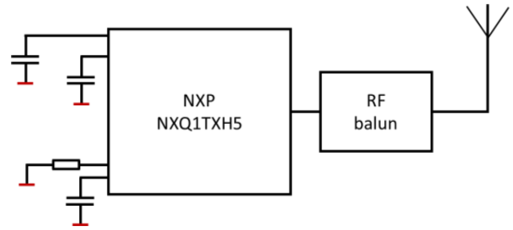

Figure 8: Wireless charging circuit

As previously mentioned the NXQ1TXH5 controls the communication and the power flow. Surrounding passive components are necessary to measure the actual power level, response from the receiver and adapt the integrated circuit (IC) to the antenna. Additional capacitors stabilize the power supply in order to get a stable power flow from the input of the resonance tank including the antenna. A micro USB type B jack is used as the main power connector.

Fig. 9 shows the construction of the PCB. The gray component is a magnetic material inlay.

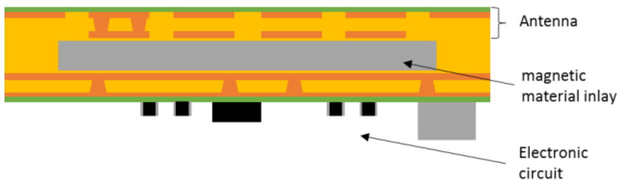

Figure 9: Stack up of PCB

The thickness of this construction (excluding the components on bottom) is set to be 800 µm while the magnetic material inlay has a size of 50 x 50 mm x 0.5 mm. Overall finished construction (including components) height is 2.4 mm.

The winding concept selected is a spiral winding structure on two layers with a resulting inductance value of 4.8 µH and a Q-factor of 17.5. During charging, the DC losses are comparably low, resulting in only 0.86W. Simulation shows that the inlay causes the H-field to distribute only to the top direction towards the chargeable device (Fig. 10).

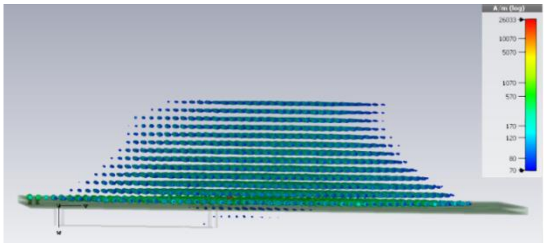

Figure 10: Field distribution

High-energy throughput is mandatory for this type of applications. Therefore, the spiral copper structure can transfer up to 8W power to a mobile device while the overall temperature rise is lower than 30°C. Special copper structure helps to distribute the heat over the whole surface of the charger to avoid hotspots in the area of the spiral winding.

The focus on this prototype was to evaluate the production process concerning the large inlay size and possible delamination problems because of less adhesion between the inlay and the PCB itself. We could show that certain material combinations work as expected and show no delamination at all. Fig. 11 shows a picture taken of the PCB with top view.

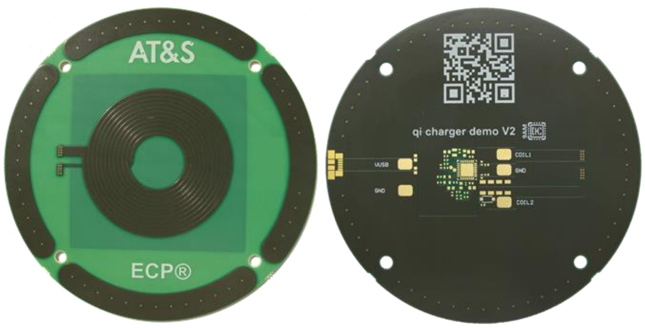

Figure 11: Wireless charging unit with magnetic inlay

D. Transformer

As discussed in chapter III, two windings on the same core with less turns results in a transformer to block DC voltage. This demonstrator build shows that such application is feasible on a surface area of 10 x 10 mm. The height of the PCB is about 1 mm. All components necessary for electrical functionality use the space on the top side of the board. A toroidal shaped magnetic inlay surrounded by two copper windings form the transformer. The bottom layer contains all electrical connections and is the mechanical interface to a second board (e.g. motherboard). This module can be processed like a standard surface mounted component.

The cross section shows the principle build up:

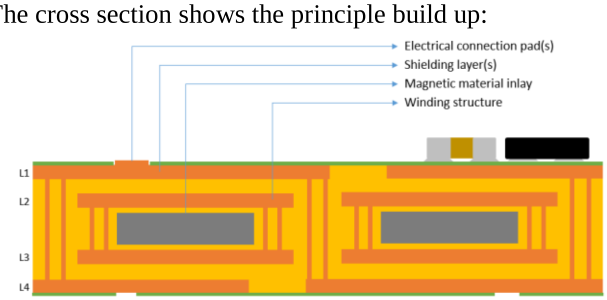

Figure 12: Construction of the transformer demonstrator

In order to achieve high coupling between primary and secondary windings, no air gap is introduced in the magnetic core. A turn ratio of 10:11 turns ensures a voltage ratio of 5V on the input to a minimum value of 5V on the output. For this application, the output remains unregulated. An additional low dropout voltage regulator helps to stabilize the voltage if needed. Due to lower copper heights of 35 µm and thermal consideration, the application is limited to 300 mA on the output. A control IC from Texas Instruments with an implemented push-pull stage drives the primary winding. A center tap on both, primary and secondary is necessary. The X-ray scan in Fig. 13 shows the magnetic inlay and the copper windings.

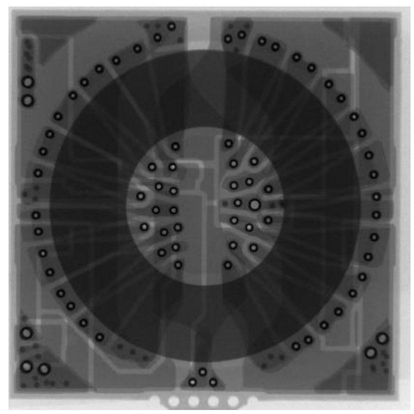

Figure 13: X-Ray of the transformer demonstrator

Figure 13 also shows the insulation path in the center of the picture. A gap of 900 µm over all layers ensures proper functionality. Simulation and measurement shows the following values for the windings:

Table 1 Results from measurement

Symbol	Parameter	Value	Deviation
L_1	Primary self-inductance	3.33 µH	3.9 %
L_2	Secondary self-inductance	3.53 µH	9 %
$R_{DC,1}$	Primary DC resistance	56 mΩ	1.8 %
$R_{DC,2}$	Secondary DC resistance	72 mΩ	5.6 %

Deviation gives the difference between measured and simulated values. As they are less than 10% the result can be considered as valid.

Figure 14 gives an illustration of the demonstrator build. On the left hand side the control IC including a power supply stabilization is located while the right hand side shows the rectifier and the necessary capacitors to stabilize the output voltage.

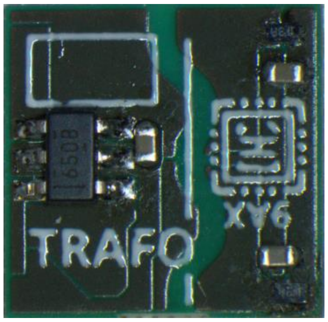

Figure 14: Illustration of the hand-assembled demonstrator

VI. Conclusion

Provided concepts show high integration factors and better utilization of printed circuit board, especially developed for power delivery. This technology is useful for inductors, transformers, magnetic shielding and more.
Next steps until the end of the project is a further investigation in reliability of the printed circuit board. At the moment, thermal cycling tests and HAST tests are ongoing.

VII. Acknowledgement

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