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High Frequency LTCC based Planar Transformer

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Abstract

As we move towards high power and higher frequency related technology, conventional wire-wound magnetics have their own limitations which has led path to the development of planar based magnetic materials. Nowadays more planar magnetic technology has been employed because it is easier to fabricate them. The planar magnetic is a transformer or an inductor that replaces the wire-wound transformer or inductors which generally uses copper wires. One of the main reasons why we move to planar magnetic technology is its operation at higher frequency which provides higher power density. This study explains in detail about the design and fabrication of planar transformer for power electronics applications.

The most important part of the transformer is its core. The cores in the planar transformer have different shapes and are available in different sizes. A planar core that is optimized, when compared with the conventional core with similar properties, exhibit better properties. In planar winding, we have different configurations available and with the optimum configuration, the losses of the transformer can be efficiently reduced.

In this work, we have considered all the design specifications and came up with an optimum design procedure in order to design a good power planar transformer. This also deals with the case where the temperature rise is higher than what the PCB can withstand and try to come up with a solution for that. The next step for the planar transformer is to move from printed circuit board (PCB) to low temperature co-fired ceramic (LTCC) substrate which is attempted in this work. The main emphasis in this work is the design and fabrication procedure of LTCC based planar transformer. Ceramic can withstand higher temperature and has a better coefficient of thermal expansion (CTE) but has its own disadvantages which are also discussed here.

Acknowledgements

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Chapter 1. Introduction

1.1 Planar technology- An overview

Nowadays, the switching frequencies have gone higher based on the application and with higher frequencies, we can achieve smaller size which will be very helpful for high power densities. For high frequency switching operations, conventional wire wound magnetic materials are not compatible, which is the reason we move to planar magnetic technology. Comparing to the conventional wire wound magnetics, planar magnetics provide better performance, smaller in size, easy to design as the windings are mostly repeatable. A lot of research work has been done which help us to benefit from the field of planar magnetics.

1.2 Advantages and disadvantages of planar technology

The winding difference between the planar and conventional magnetic material can be understood from Fig. 1 and Fig. 2. As it is observed from the figure, planar magnetics have low profile cores compared to the wire wound magnetic. Also, the windings of the planar transformer are flat on the surface of printed circuit boards. Windings of the planar transformer can be in different shape which will affect the copper loss of the transformer.

Fig. 1. Conventional transformer. [Image by author]

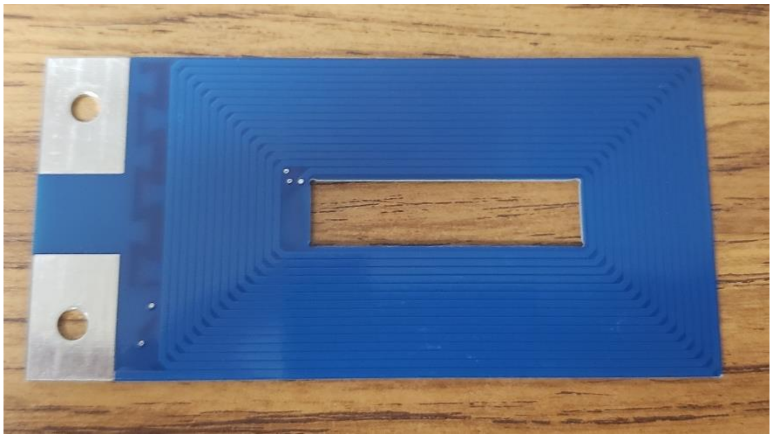

Fig. 2. Winding layer on PCB of a planar transformer. [Image by author]

There are lot of advantages and disadvantages of planar transformers over conventional wire wound components. They include as follows:

1) *Lower leakage inductance*: Arrangements of the windings have an effect on the leakage inductance. In planar transformers, there are usually two types of arrangements such as interleaving and non-interleaving. Example of the interleaving arrangement is P-S-P-S-P-S and so on based on the number of boards. This type of arrangement can be easily done in planar transformer which helps in reducing the leakage inductance.

2) *Low profile structures*: As said earlier, planar transformers have low profile core structures which indicates that the volume of the transformer has been used effectively and also provides higher power densities which are key factors when operating at higher switching frequencies.

3) *Good repeatability*: The design of windings are very easy as you just have to repeat the same. Repeatability of components helps a lot not only in the design perspective but also during resonant topologies.

4) *Ease of fabrication*: Since planar magnetics are designed on the printed circuit boards (PCB), the fabrication process is quite easy and familiar. Also, another important aspect is PCBs are relatively less expensive.

We have talked about the advantages of the planar transformer but there are always some limitations for everything. The disadvantages are as follows:

1) *Increased parasitic capacitance:* Since we are stacking windings one on top of the other, there is always some air gap which results in the increase of parasitic capacitance. This is a very big disadvantage that will affect the performance of the transformer. In order to minimize this, we might have to reduce the air gap to the lowest as possible.

2) *Higher operating temperature:* Since the frequency is higher, the reactance ($2\pi fl$) of the transformer increases along with that. As the reactance increase, the heat dissipation will also increase which is why the operating temperature is very high compared to the conventional wire wound transformers.

1.3 Aim of this work

This study is done in order to analyze the performance of planar transformers. Halfway through the work is when we realized PCB are not the best materials to use at high temperature.

So a new methodology was employed in the planar magnetic technology. This study talks in detail about the design procedure of planar transformers in general, different winding arrangements that are used, electrical characterization of those transformers such as using impedance analyzer. This study also talks in detail about the design and fabrication procedure of low temperature co-fired ceramic (LTCC) based transformers.

1.3.1 Chapter 2: General design procedure

In this chapter, we talk about the calculations that are required in order to design a transformer. This chapter also talks about the general design procedure, what are all the core materials available, basic construction of a planar transformer. There are 3 important parts in a planar transformer which include core material, windings on PCB and the insulation. This chapter talks about the assembly of the transformer, different core geometries available, different windings shapes and sizes. The information from this chapter is not particular for any design specification but can be extrapolated in order to design any planar transformer.

1.3.2 Chapter 3: Planar transformer construction

For the construction of a planar transformer, the most important part is the windings on the PCB. There are two sides just as in the conventional transformer, primary and secondary. Based on the power requirements, windings on both the sides may vary. If the windings in the secondary side of the PCB is higher, it is a step-up transformer and step-down transformer if it is vice versa. The dimensions of the PCB vary according to the dimensions of the transformer core that we select. Planar transformer cores are mostly manufactured by Ferroxcube [7]. So with the assumption of core material, the dimensions of PCB and the windings on PCB are calculated and the fabricated. These transformers were then characterized electrically.

1.3.3 Chapter 4: LTCC based planar transformer model

To overcome the disadvantages and challenges from the PCB model, we are attempting to move to LTCC based planar transformer model. Similar to the PCB model, LTCC also has primary and secondary boards connected by transformer core in the top and the bottom. The manufacturing process is different from that of the PCB which is explained in detail in this chapter. Designing and fabricating the LTCC planar transformer is explained in detail as that is the main aim of this study. Comparison of both the models is done with various aspects that include assembly of the transformer, design changes, manufacturing process. A Bode analyzer was used on both the transformers in order to get the characterization of parameters such as inductance and impedance as how it changes along with the frequency.

Chapter 2. General design procedure

2.1 Planar transformer basic construction

The basic construction of a planar transformer is very similar to that of the conventional transformer. As the basic operation of transformer is still valid for the planar transformer, construction and components becomes very similar in both the transformers. Just like a conventional transformer, this also has core, windings and insulation. The core can be two halves, one on the top and one on the bottom. In between these core halves, windings are placed. Windings are designed over the PCB instead of Litz wire. There are primary and secondary windings. Based on the specifications required, number of turns on each winding can vary. There is also insulation provided between the windings.

One of the biggest challenges of transformer is selection of material based on our specification. When it comes to planar transformer, it is even a bigger challenge as the operating frequency is very high, almost around 100kHz. So in this chapter, we will see about the different types of core available, PCB windings and how to assemble the transformer.

2.2 Core material

Core material of the transformer is generally Ferrite. Nowadays, for transformers FerroxCube manufactures core materials that are widely used all over the world. There are some factors which contribute in deciding the core material for our transformer such as the dimensions of the core, shape, quality of ferrite used, and magnetizing length. We get different shapes of core material from Ferroxcube such as EE, EI and ER type. In Fig. 3 and Fig. 4 we can see some of these core types available in different shapes. Some examples of Ferroxcube core types are 3C92, 3C94, 3C95, 3E6, 3E10, 3E15 and so on. Based on the dimension of these core materials only, we will be able to design our PCB windings so that they will fit perfectly between the cores.

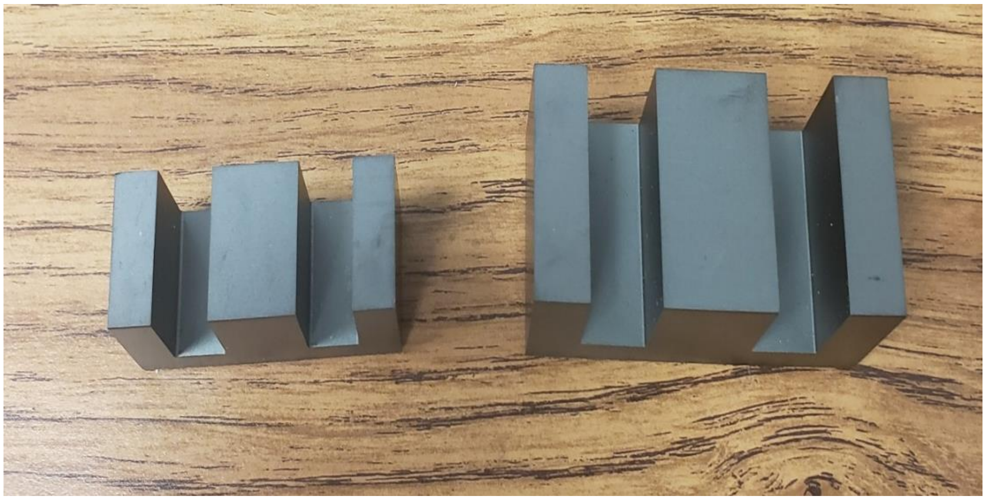

Fig. 3. Examples of Ferroxcube EE type cores. [Image by author]

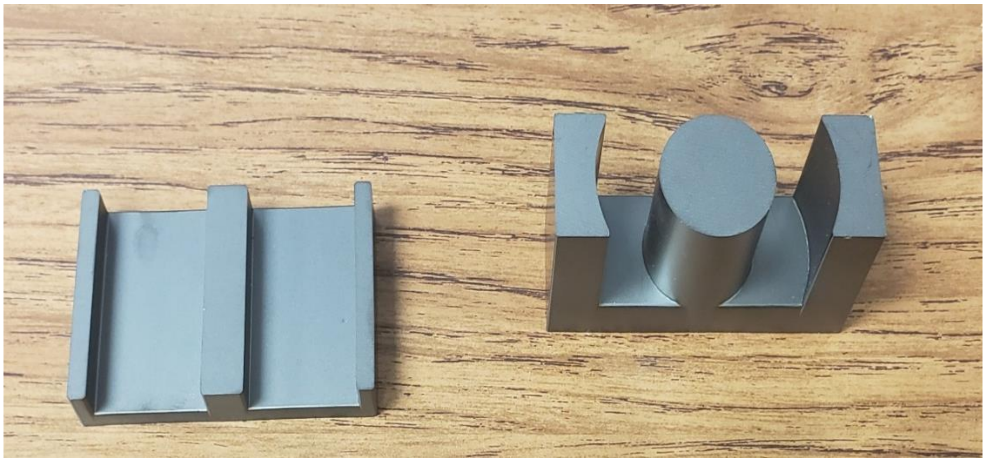

Fig. 4. Examples of Ferroxcube EI an ER type core. [Image by author]

2.3 Windings on PCB

The big difference between the two types of transformer is the configuration of their windings. Instead of Litz wire, we design the windings on PBC as per requirement. There are two types of traces based on the current carrying capacity of the windings. If the board has to carry more current, then the copper winding on the board has to be thicker and it is called as high current trace as shown in Fig. 5 which has copper of about 18mm thickness.

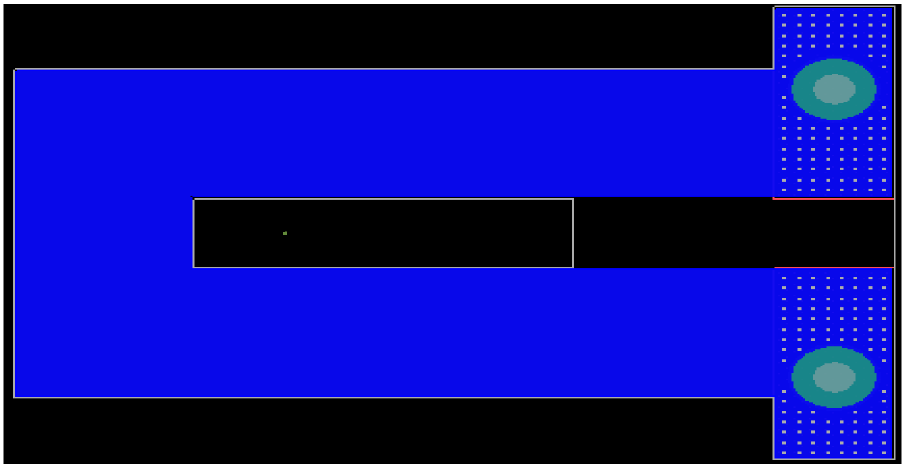

Fig. 5. PCB windings- high current trace. [Image by author]

If the board has to carry less amount of current, the winding does not have to be thick. These types of traces are called low current trace as shown in Fig. 6 which has copper of 1mm thickness. Based on the specifications, these traces can be considered as primary or secondary board of the transformer. If it is a step up transformer, then high current trace can be considered as primary and low current trace as secondary. These traces can be drawn using any PCB Editor software.

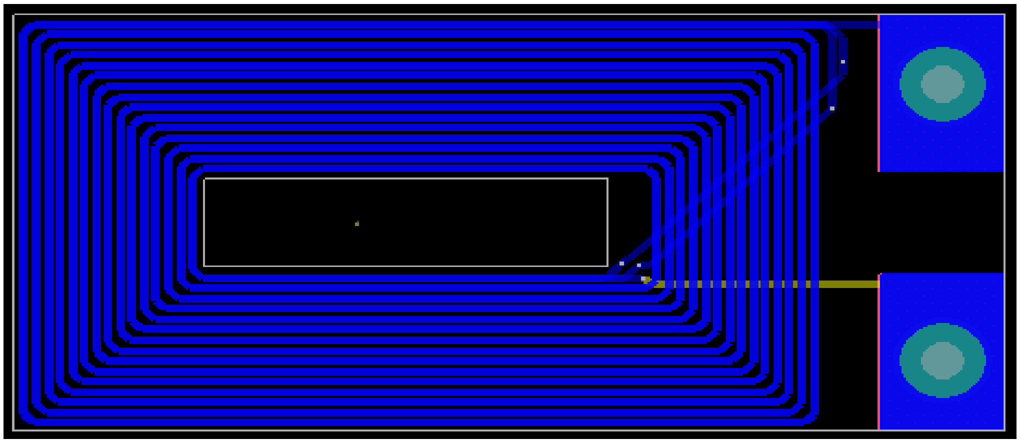

Fig. 6. PCB windings- low current trace. [Image by author]

2.4 Mounting of the core and assembling the transformer

There are several ways in which core can be mounted. As we said there are two halves of core and they have to be stuck together in some way so that they don't move during the operation of transformer. Since we are talking about high frequencies, vibrations created will be huge and we have to use a really good means of mounting the two halves of the core together.

One of the most convenient ways of core mounting is using epoxy adhesive to stick the core together. One of the most commonly used epoxy adhesives is 3M EC- 2216A/B. Other than using some kind of adhesive to stick the core halves together, some kind of tape that can withstand high temperature and vibrations can be used. In this study, Kapton and insulation tape has been used in order to tape the core halves from moving.

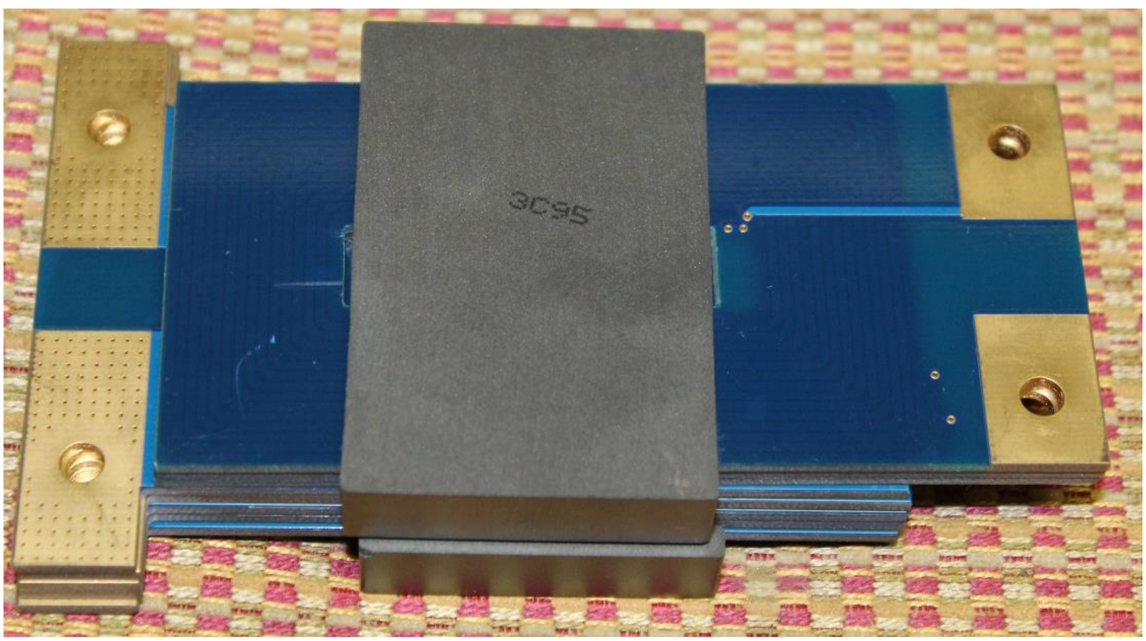

Fig. 7. Example of core mounting and assembling the planar transformer. [Image by author]

Also, we are not using just one of primary and secondary boards, but multiple boards. In that case, we have to use something to attach these boards together. In this case, we are using non-interleaving arrangement, which means all the primary boards are stacked together and all the secondary boards are stacked together. For stacking these boards together, we have used screws and nuts. This ensures that there is connection established between the windings and also the boards do not move with the vibration of transformer.

Chapter 3. Planar transformer construction

3.1 Design specifications

The width and height of the converter is 120mm x 40mm. The transformer that we design has to be within the above mentioned dimension so that it fits within the converter. So planar transformer is the only way to do this. The trick to handle is the designing of a transformer that can handle the power and high input current without saturating.

Before we start with the design of the transformer, there are some assumptions that we have to make:

- Core material: 3C95 (has flat loss 25C-100C)
- U_i = 3000 (relative permeability)
- B_{sat} = 0.53 T

Calculation of the cross section of transformer:

We can now walk through the calculation of the need cross section of the transformer to meet the saturation flux density requirement.

Choose peak flux density to be 0.2T (give headroom and minimizes losses)

$$volt - seconds \rightarrow \lambda = \int_{t_1}^{t_2} v_t(t)dt \quad (3.1)$$

Where, in the worst case operating condition, V_{peak} applied to transformer is 36V for half of switching period ($t_2 - t_1 = T_s/2$, coincides with 50% duty cycle). Therefore, the solution to the volt-seconds applied to the transformer is:

$$\lambda = \int_0^{\frac{T_s}{2}} 36\, dt = 36 * \frac{T_s}{2} \quad (3.2)$$

For f_S = 250 kHz → T_S = 4us and T_S = 2us. Therefore:

$$\lambda = 36V * \frac{4us}{2} = 72e^{-6}\ volt - seconds \text{……………………....…….. (3.3)}$$

Now we can find the needed cross sectional area to satisfy our peak flux density requirement (ΔB=0.2 T):

$$\Delta B = \frac{\lambda}{2n_p A_c} \text{……………………………………………………… (3.4)}$$

Where n_P is the primary turns and A_C is the cross sectional area of the core. Because of the large currents on the primary, we would like to keep the primary turns as low as possible – 1turn would be ideal. Therefore:

$$A_c = \frac{\lambda}{2n_p \Delta B} = \frac{72e^{-6}\ volt - seconds}{2*1\ turn*0.2T} = 1.8e^{-4}\ meters^2 \rightarrow\ 180\ mm^2 \text{………… (3.5)}$$

With a minimum cross-sectional area of the transformer being found to be 180 square millimeters, we can say that we can find a transformer core that will suite this requirement based on the availability from Ferroxcube.

Overall, we can design this transformer because the flux density is based on the volt-design balance and not the winding current. So, our next problem is to solve the need for large windings to handle the large primary currents.

3.2 Design procedure

3.2.1 Primary winding requirements

The peak input current for the converter is 465A. With the full- bridge topology, this means that peak currents in the primary will reach ~ 900A! However, we are only concerned with RMS value of the current, which is 465A, when designing the windings for thermal and ampacity performance.

Because of the high frequency effect in windings (known as the skin effect), we need to find the area of the total winding copper and the maximum size of an individual conductor. Additionally, because this is a planar transformer, we will try to use either copper bussing or PCB windings to maximize our geometry. We will try PCB windings first because of the ease of use and manufacturability! An online calculator (www.4pcb.com/trace-width-calculator.html) was used to find the required trace width in a PCB for a given copper pour weight (e.g. 1oz/ft^2), desired temperature raise in the windings, and a given RMS current.

Next we have to think about minimizing height of the winding because of the low-profile of the transformer. To do this, we should look to order from JLCPCB (https://jlcpcb.com/) because they offer 6-layer, 2oz/ft^2 copper PCBs in large quantities. For 6 layers, at 2oz/ft^2 per layers, the total weight of a winding housed in a single PCB is 12oz/ft^2. This is to say that an RMS current of 465A is split between 6 different winding at 2oz/ft^2 per winding (77.5A per winding layer in the PCB). Using the calculator described above we can find the total number of PCBs needed to have a traced width that is less than the window area of a reasonable size planar transformer core. The following list of required trace widths is found using 10°C temperature raise and 465A RMS current:

- 1 PCB (77.5A per winding layers) – trace width = 158 mm
- 2 PCB (38.75A per winding layers) – trace width = 60.6 mm
- 3 PCB (25.83A per winding layers) – trace width = 34.6 mm

- 4 PCB (19.375A per winding layers) – trace width = 23.3 mm
- 5 PCB (15.5A per winding layers) – trace width = 18.1 mm

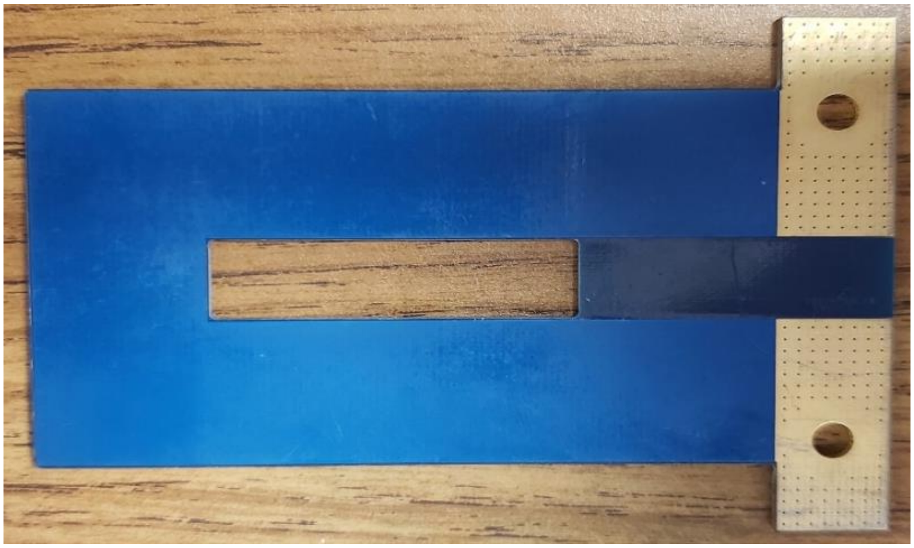

Fig. 8. Primary winding in PCB. [Image by author]

In the primary winding PCB, both the front and back view are similar as it has only one winding. Resistance was measured for the primary winding and from the design, we know that it has to be very low as it is one big piece of copper winding connection. Ideally, the resistance has to be 0 but in our case it was found to be 0.1Ω. The resistance is same for all the primary winding and we are using 4 boards in parallel, hence the total resistance is 0.025Ω. Since this board has high current trace, the resistance will be lower than that of the secondary board.

3.2.2 Secondary winding requirements

Next we need to find out if we can fit all of our windings inside the window area of this core. To do this, we will find the total cross section of our PCB windings for both the primary and secondary. To do this, we need to evaluate the secondary side winding size like we did with the primary.

Next we need to know how many turns we need for the secondary winding. Given loss estimates from the previous discussions and the voltage drop associated in all the copper in the system, we should probably target a winding rate of 1:40-1:50. Let us say we need 1:45 turns ratio with 15 windings per PCB in a total of 3 PCBs (3PBCs * 15 windings/PCB = 45 windings). Remember that we will be using a single winding on the primary to minimize copper losses.

So, in total we have 5 PCBs on the primary and 3 PCBs on the secondary to meet our current carrying requirement and our turn ratio requirement. We can order PCBs from JLCPCB with a thickness as low as 0.4mm and as high as 2mm. Our window height is 21mm and we need to leave room for insulation like Kapton tape.

For 8 total PCBs, here are the total heights of the PCBs stacked for different PCB thicknesses:

- 0.4 mm thick = 3.2 mm
- 0.6 mm thick = 4.8 mm
- 0.8 mm thick = 6.4 mm
- 1.0 mm thick = 8 mm
- 1.2 mm thick = 9.6 mm
- 1.4 mm thick = 11.2 mm
- 1.6 mm thick = 12.8 mm
- 1.8 mm thick = 14.4 mm
- 2.0 mm thick = 16 mm

From the above calculations, we can see that any PCB thickness greater than 1.4mm will not fit inside the winding area of the core.

Fig. 9 (a). Secondary winding in PCB- top layer. [Image by author]

Fig. 9 (b). Secondary winding in PCB- bottom layer. [Image by author]

For the secondary winding the resistance was measured and it was found to be 8Ω. Since we are using three secondary layers in series, the resistances add up and the total resistance of the secondary layer was 24Ω. The secondary voltage is around 625V and the secondary current is 12A. So, the transformer is rated to operate around 7.5kVA.

3.2.3 Core selection

There are several planar transformers from Ferroxcube that have window area widths that would accommodate 23.3mm or 17.1mm widths.

The E58/11/38 transformer core meets the spacing requirements discussed previously. A transformer made with two of these cores stacked one on top of the other would have the following parameters:

- Width = 58.4 mm
- Height = 21 mm
- Depth = 38.1 mm
- Window width = 20.95 mm
- Window height = 13 mm
- Window area = 272.35 mm^2
- Cross sectional area = 310 mm^2
- Volume = 41600 mm^3
- Magnetic length = 165.4 mm

Fig. 10. Core halves - top and bottom view. [Image by author]

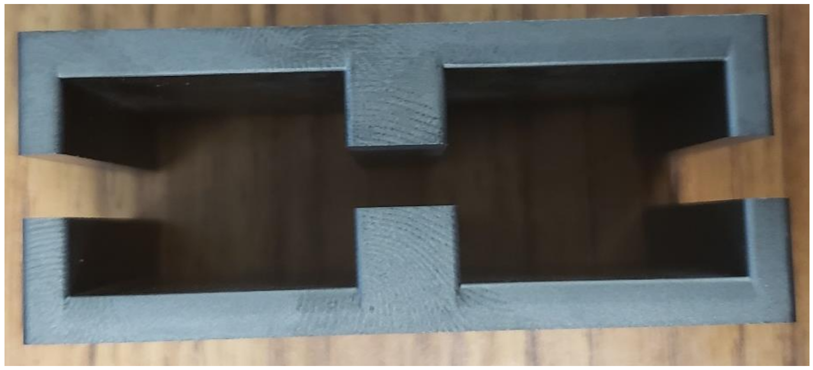

Fig. 11. Planar transformer core- perspective. [Image by author]

From the above parameters we can see that this core meets the required cross-sectional area requirement and the window width requirement based on our winding width calculations – we would need 5 PCBs ideally but we can probably get away with 4 PCBs.

3.2.4 Transformer core loss analysis

The loss estimate is made using the Steinmetz equation:

$$P_v = k f_s^{\alpha} \Delta B^{\beta} \quad \left(\frac{w}{m^3}\right) \ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

Where f_S is the switching frequency, ΔB is the peak flux density, P_v is the volumetric power losses in watts per cubic meter, and k, α and β are material parameters found by curve fitting the flux-volumetric loss plots in the material datasheet. For 3C95 (our selected magnetic material from Ferroxcube), these parameters are found to be:

- k = 0.029
- α = 1.74
- β = 2.4

For the core selected (E58/11/38), with a volume of 41600mm^3, cross-sectional area of 310mm^2, and a primary turn of 1, the peak flux density can be found:

$$\Delta B = \frac{\lambda}{2n_p A_c} = \frac{72e^{-6}\ volt{-}seconds}{2*1\ turn*310e^{-6}m^2} = 0.116\ T \ldots\ldots\ldots\ldots.. (3.7)$$

This peak flux density is within the range of the saturation limit of the transformer core material.

Next we look at the losses based on the Steinmetz equation.

$$P_{core} = P_v * Volume = (41.6e^{-6}m^3)kf_s^{\alpha}\Delta B^{\beta} = 16.62\ Watts \ldots\ldots (3.8)$$

3.3 Assembly of the planar transformer

The parts of the planar transformer are core, the windings and the insulation. The arrangement of planar transformer is similar to that of the conventional wire wound transformer. The windings are placed in between the core and they are separated by insulating material such as FR4 as shown in Fig. 12.

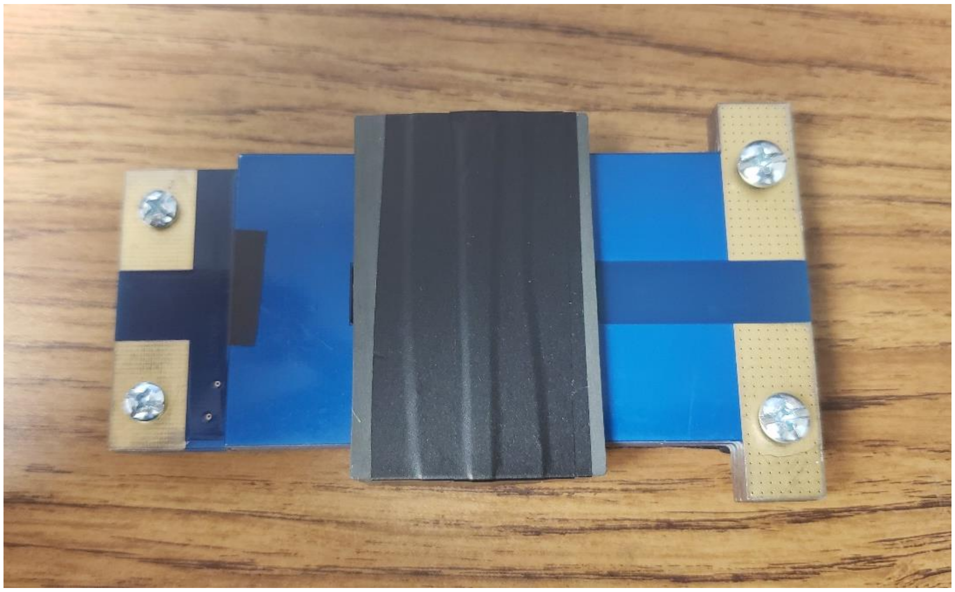

Fig. 12. Assembled planar transformer- top view. [Image by author]

The core that is used in this work is EI type core. There are two parts of the core and one is placed on the top and the other is placed on the bottom. The primary windings are placed toward the top half of the core and secondary windings are placed towards the bottom half of the core.

The windings for the transformer were designed using a PCB Allegro software. First, a simple schematic is drawn and then we start with the design. First we use the measurements of the board that we require. We need to create a hole in the center of the board so that the cores can fit in. After that we select the material and then start drawing. PCB Allegro was chosen as it is one of the easiest softwares to use for PCB design. In PCB Allegro, we can get the data of how much the film area was deposited on the board, amount of etch used and much more.

Fig. 13. Assembled planar transformer – side view. [Image by author]

In order to reduce the stress of the overall transformer, a new auxetic pattern, designed by Mahsa Montazeri [16] was deployed in the windings of the transformer. We did the simulation in Ansys after adding the auxetic pattern and it proved to be significant. The stress was reduced by

56% and the temperature was reduced by 30°C on the transformer which is shown in the Fig. 14 below.

Open circuit and short circuit tests were performed on the transformer. In the open circuit test, one side of the transformer is connected to the variac or auto-transformer and the other side is usually open ended. So in this case, the secondary side of the transformer is connected to the variac as primary side is basically shorted and draws huge amount of current. A clamp ammeter is connected with the secondary side of the transformer in order to measure the input current and another multimeter is connected to the secondary side in order to measure the output voltage. Input voltage can be verified from the variac. From the open circuit test, we determine the core loss at no load current.

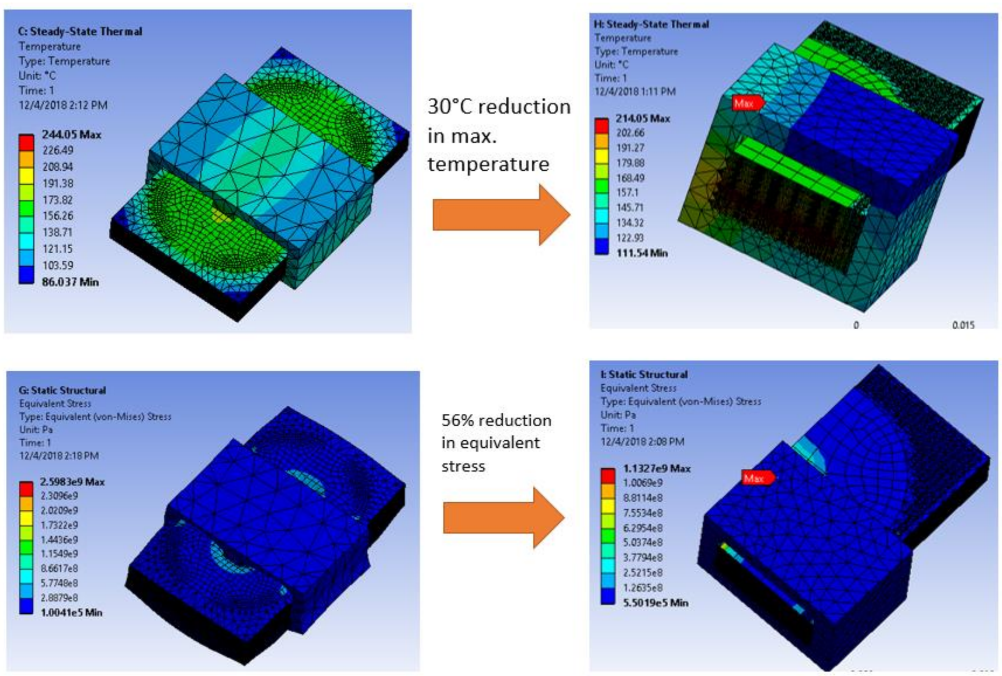

Fig. 14. Simulation results of temperature and stress distribution with auxetic pattern [16].

For short circuit test, the arrangement is similar except the primary side is short circuited. Since the voltage applied will be negligible when compared to the rating of the transformer, core loss can be neglected and the power dissipated is all considered as copper loss. The arrangement for the test is shown in Fig. 15 below.

With the below arrangement, the input voltage was set to be 30V. Since the resistance of the secondary windings is 24Ω, the input current was 1.25A. The load resistance was 25Ω but the output voltage proved to be very low which was around 0.2V. This was the result for the open circuit test which indicates that there is some core loss associated with the transformer.

Fig. 15. OC testing arrangement for the planar transformer. [Image by author]

3.4 Challenges with planar transformer

With the PCB based planar transformer, we face a series of challenges. We move from conventional transformer to the planar transformer because it is compact, easier to design and can operate at higher frequencies. But when we operate at high frequencies there are some challenges which we have to overcome in order to optimize the transformer and make it more efficient.

There are two types of losses associated with the transformers and they are core or iron loss and winding or copper loss.

As the name suggests, the power loss in the core area is the core loss. There are two subcategories in the core loss. They are Hysteresis loss and the Eddy Current loss.

Hysteresis Loss

Hysteresis loss is caused when the direction of the magnetization in the transformer core is reversed and depends on the quantity and quality of the ferrite used and frequency at which the reversal magnetization occurs.

Soft core materials can be used in order to reduce the losses due to hysteresis. Examples of some soft magnetic materials are Mn-Zn, steel alloys and so on. These soft magnetic materials possess utmost permeability, high saturation magnetization and slight coercive force.

Eddy current Loss

To explain eddy current, we have to understand the basic operation of the transformer. When the primary side of the transformer is connected with the AC power source, a flux is created in the primary winding which gets linked to the secondary winding with the help of the core. This produces an emf in it. When a part of this magnetic flux links with some other conducting part, it induces an emf causing small circulating current in them which is called Eddy Current. Due to these currents, some energy will be dissipated in the form of heat.

Eddy current loss occurs mainly due to the core material. So to reduce the eddy current loss, we can use stacks of small and thin magnetic cores instead of using a single block. Also laminating the core material and providing proper insulation will help in reducing the losses due to eddy current.

Copper or winding loss

The type of loss that occurs in the winding is called winding or copper loss. This is also called as I^2R loss, which is due to the resistance of the transformer windings. Copper loss for the primary winding is $I_1^2R_1$ and for the secondary winding is $I_2^2R_2$ where I represent the currents and R represents the resistances. 1 and 2 indicated the primary and secondary windings respectively. It is evident from the above mentioned equations that copper loss is directly related to the square value of current. As we all know, current depends on the load, hence copper loss varies according to the load.

In order to reduce the copper loss, the windings can be made thicker. As we know, resistance is inversely related to the square of the thickness, making the winding thicker reduces the resistance which in turn will reduce the copper loss.

Operating at high frequency can make the transformer to reach higher temperature such as 150°C - 200°C. This operating temperature is not feasible as the printed circuit boards cannot withstand that temperature and sometimes, they tend to melt. So the biggest challenge is to dissipate the heat especially from the core of the transformer. Just like the conventional transformers, we can try using heat sinks or liquid coolants in order to reduce the temperature of the heat dissipation. But that would still create another problem. PCBs do not have good coefficient of thermal expansion (CTE) and there is always a compatibility challenge when we are using PCBs. In order to overcome both of these challenges, a new methodology is employed which is explained in detail in the next chapter.

Chapter 4. LTCC based planar transformer model

4.1 Introduction

As explained in the previous chapter, there are some limitations when we are using a PCB based transformer model. In order to overcome them, we are moving to a ceramic based transformer as they have better thermal properties when compared to the PCB. The ceramic that we have used in this process is low temperature co-fired ceramic (LTCC). The LTCC ferrite cores in combination with the silver conductor that is printed on the screen produces small size transformers without any wires. The LTCC transformers consist of ferrite core which is a conductor and also a magnetic material and an insulator which helps in the integration of a single device which is smaller in size and has a very low profile.

Because of the fabrication process, they can handle temperatures of up to 300°C [22]. Since the LTCC fabrication process can combine the windings within one solid ceramic unit, these transformers can withstand higher vibration and thermal cycling.

4.2 Proposed design

Similar to PCB, a multi-layer ceramic is used in this process. A 6 layer LTCC is used for both primary and secondary windings of the transformer. The design that is used for LTCC is also similar to that of PCB. The secondary LTCC board design is same as that of the secondary PCB but there are slight changes in the primary LTCC board. In the primary PCB we had copper on all the 6 layers where as in the LTCC board, we have copper only on the top and the bottom layers while they are connected through vias. The design for LTCC is done using AutoCAD software. The dimensions of the primary and secondary boards are shown in Fig 16 (a) and (b) respectively.

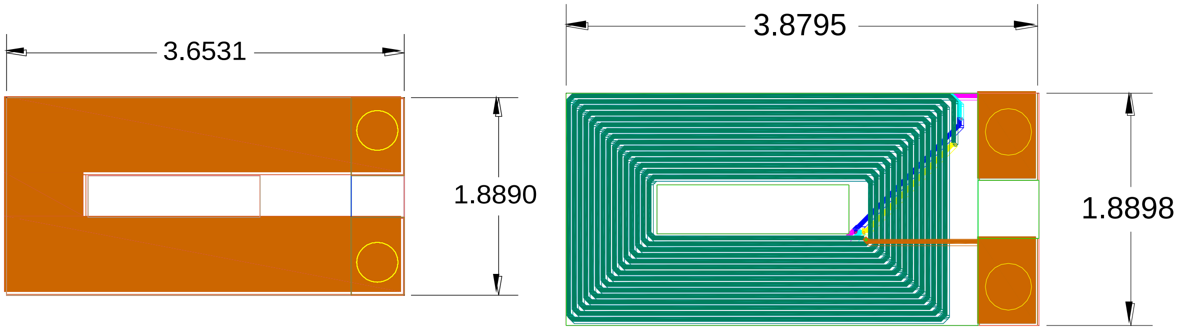

Fig. 16. (a) Primary LTCC board dimension (b) Secondary LTCC board dimension. [Image by author]

In the top and bottom of boards, solder mask is applied in order to prevent oxidation of the material. 2D design for the stack of multi-layer boards are shown in Fig. 17 and Fig. 18 for primary and secondary respectively.

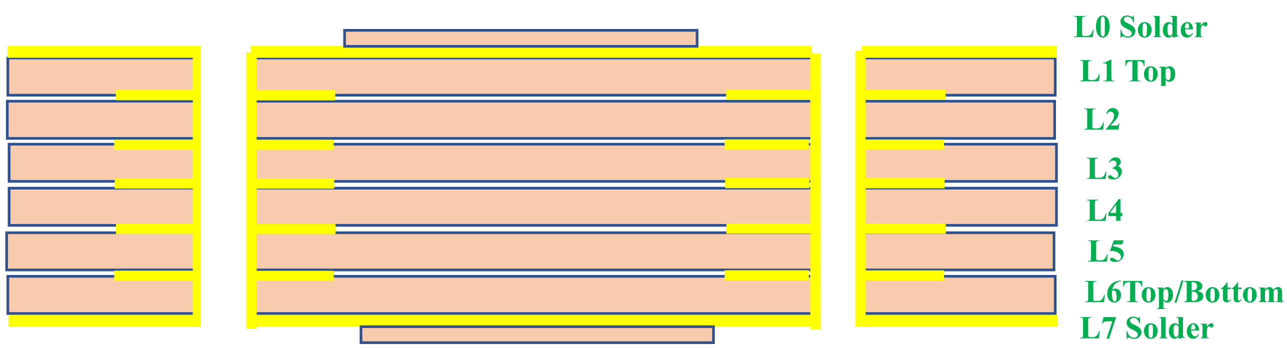

Fig. 17 2D design of primary LTCC board. [Image by author]

The yellow color represents the copper windings and as you can see in the primary board, there is copper only in the L1 Top and L6 top/bottom. The other layers in between do not have any copper windings but they link the top and bottom layers using vias.

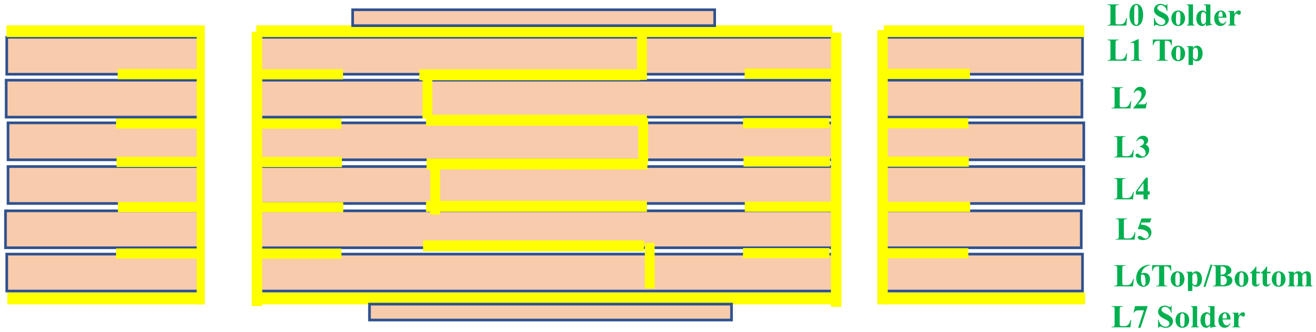

Fig. 18 2D design of secondary LTCC board. [Image by author]

In the secondary board, there is copper in all the individual layers from L1 top to L6 top/bottom. The design for the individual layers in primary and secondary boards are shown in Fig. 19. Once the design is ready, fabrication of ceramic was done in the HiDEC LTCC Laboratory. The fabrication steps are explained next.

Fig. 19 Individual layer design for primary and secondary board. [Image by author]

4.3 Fabrication procedure

Fabrication of LTCC is a little complicated when compared to that of the PCB. There are 4 steps involved in the fabrication process. Firstly, before entering in to the fabrication process, we have to select what type of ceramic material we are going to use. In this case, we have used Dupont GreenTape 9k7 LTCC because it has lot of advantages such as superior high frequency performance, demonstrated reliability, smaller package size and stable in harsh environments. Tables I and II shows the electrical and physical properties of 9k7 green tape that is used in this process.

4.3.1 Punching vias

Since this is a multi-layer design, punching vias is a very important step as they help us establish connection from the top and the bottom layers. A multi punching machine MP-4150 was used to punch vias on the ceramic green tapes. Fig. 20 shows the multi punching machine used. This machine is connected to the computer which has a software where you can specify the size of via and the location as where you need that via. You cannot specify the size of via to be less than 2mils in this machine. So based on your design, you can specify number of vias and their respective positions to punch them on the ceramic green tapes.

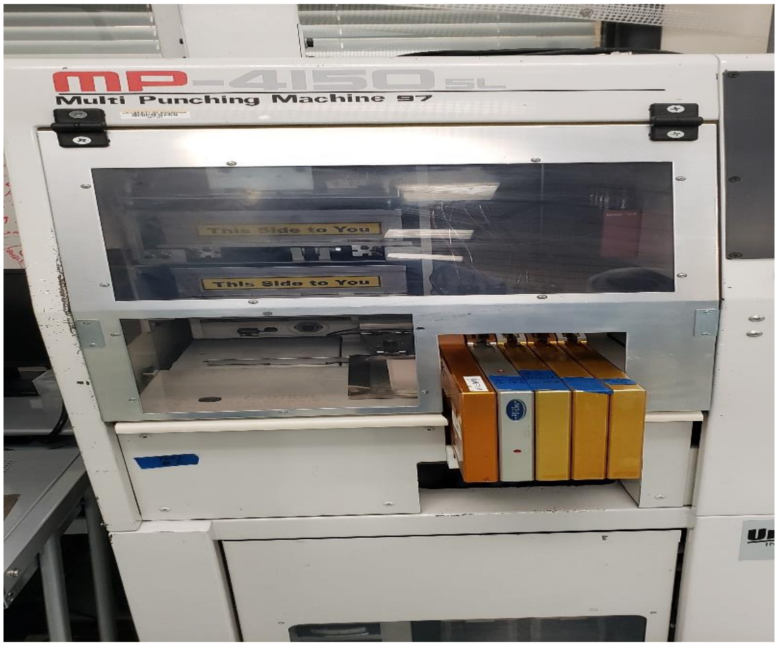

Fig. 20. Multi punching machine – MP-4150. [Image by author]

Since the primary and secondary boards are not big, we had both the boards designed on the same ceramic plate. This means the number of ceramics used is reduced by half which is cost effective. Fig. 21 shows an example of first layer of primary and secondary boards on the same ceramic plate with vias punched.

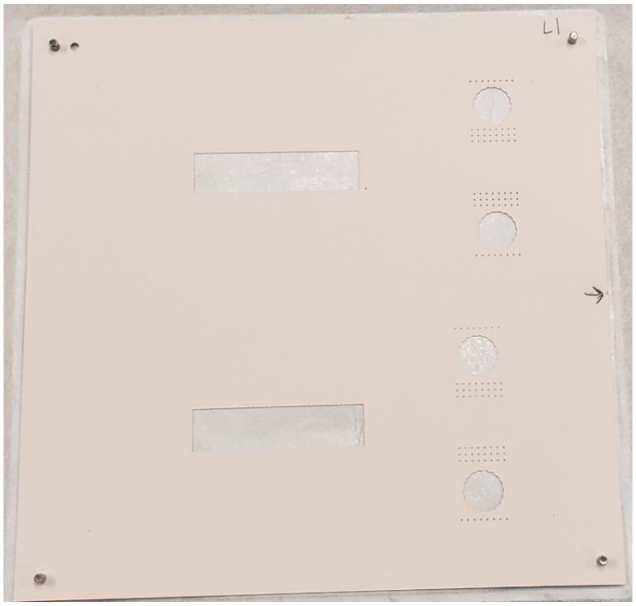

Fig. 21. Layer 1 of primary and secondary LTCC board with via. [Image by author]

4.3.2 Via filling

The vias that are punched have to be filled with some paste in order to make a connection between the layers. The via pastes are exclusively made in order to fill. A sheet of coated tissue paper is placed under each green sheet prior to the via fill step to prevent contamination and damage to the porous vacuum stone.

Via paste that is used in this process is DuPont LL601. This is a silver via fill composition specifically designed for use in high volume via filling process. A sheet of tissue paper is kept under the DuPont tape punched with vias. For certain layers, particular vias do not have to be filled with LL601, so for those particular vias, a tape is stuck over them before via filling process. A squeegee is used in order to apply via paste on the sheet and it is squeegeed to fill via holes. A microscope is used in order to check if all the required via holes are filled with the paste or not as it might not be visible with the naked eye. Fig. 22 shows the process of via filling done inside the clean room.

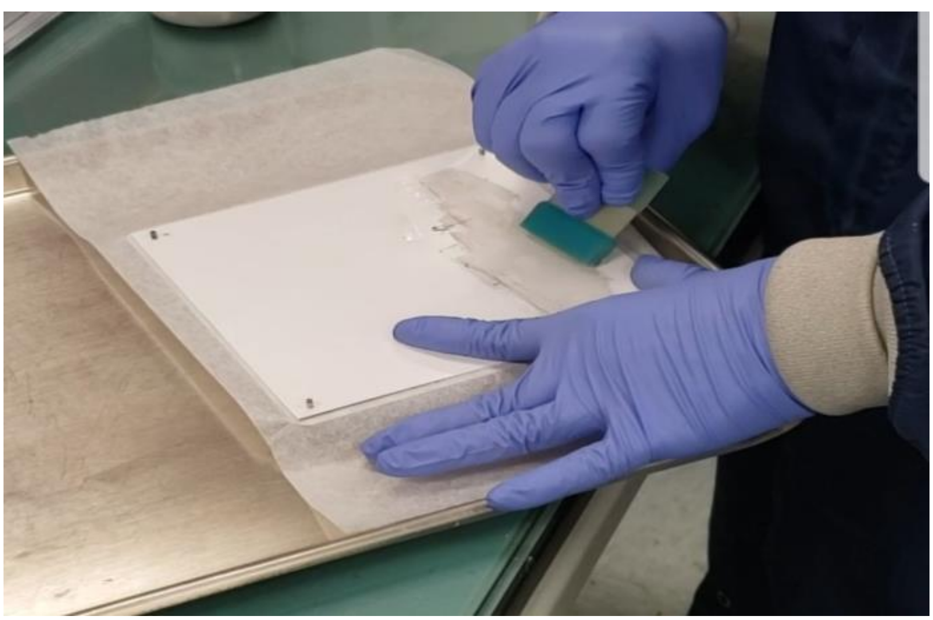

Fig. 22. Via filling process done with LL601 via paste. [Image by author]

4.3.3 Printing

After the via filling process conductor printing is done. Conductor printing is performed using a conventional thick film screen printer with mechanical registration or an automated vision alignment system. Print screens are standard emulsion type used for conventional thick film screen printing. A porous stone is used to hold the tape in place during the printing sequence as a little movement of the screen on either direction could entirely modify the design specification.

DuPont LL612 is the conductor used in the process which is a co-fireable silver signal line conductor used exclusively in the DuPont 9k7 LTCC process system. The composition is cadmium free. DuPont LL612 is directly printed on GreenTape 9k7 sheets using appropriate thick film screen printing methods with support structures to secure the sheet to the printer's stage plate. Printing is typically performed using a 325 mesh, stainless steel screen with a 10 to 12 micron emulsion thickness. Fig. 23 shows the printer that is used in the LTCC printing technology.

Fig. 23. Thick film screen printer for LTCC printing technology. [Image by author]

4.3.4 Lamination

After the conductor printing is finished drying of the sheet has to be done. Conductor prints are allowed to level for 5 to 10 minutes at room temperature and then they are kept in a well ventilated oven for about 5-10 minutes at 80°C to dry. Inspections of the printed green sheets can be performed with the zoom microscope that has a good light source. Low angle, oblique lighting is recommended to prevent a white-out of the surface features.

There are two types of lamination methods available for LTCC fabrication.

- Uniaxial Lamination
- Isostatic Lamination

Both the lamination methodologies are very similar in terms of the temperature and the time. It is around 70°C for 10 minutes. Uniaxial lamination is performed in a hydraulic press whereas the isostatic lamination is performed with heated water.

In uniaxial lamination the die is rotated 180° after 5 minutes whereas there is no need for such in the isostatic. In isostatic, the parts are put inside a waterproof bag and taped in order to prevent the water entering and damaging the part of ceramic which is not necessary in the uniaxial lamination.

4.4 Assembly of the LTCC based transformer

One of the biggest challenges with the LTCC based transformer is the assembly. The assembly is similar to that of the planar transformer but has its own limitations. Just like the planar transformer, there are two core halves, one in the top and bottom with the LTCC layer containing the windings in between them.

Ferroxcube 3C95 EI type core that was used for planar transformer is used in the LTCC transformer as well. Both primary and secondary windings are fabricated as per the design mentioned in Chapter 4.2. Figs. 24 (a) and (b) shows the images of LTCC primary and secondary windings respectively. DuPont QM44 insulation is applied on top of the windings in order to provide some insulation. Resistance of the primary winding was measured to be around 0.1Ω and for secondary winding it was measured to be around 48Ω.

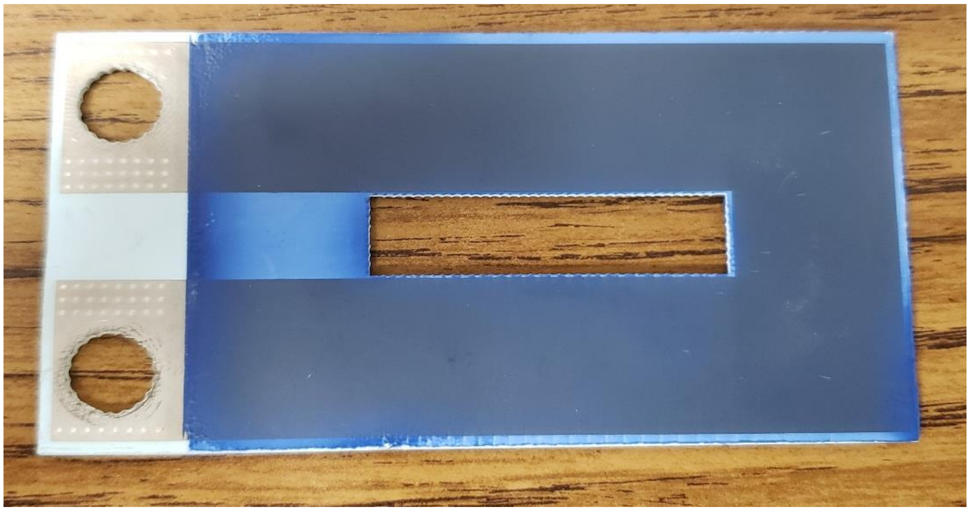

Fig. 24 (a) LTCC primary winding. [Image by author]

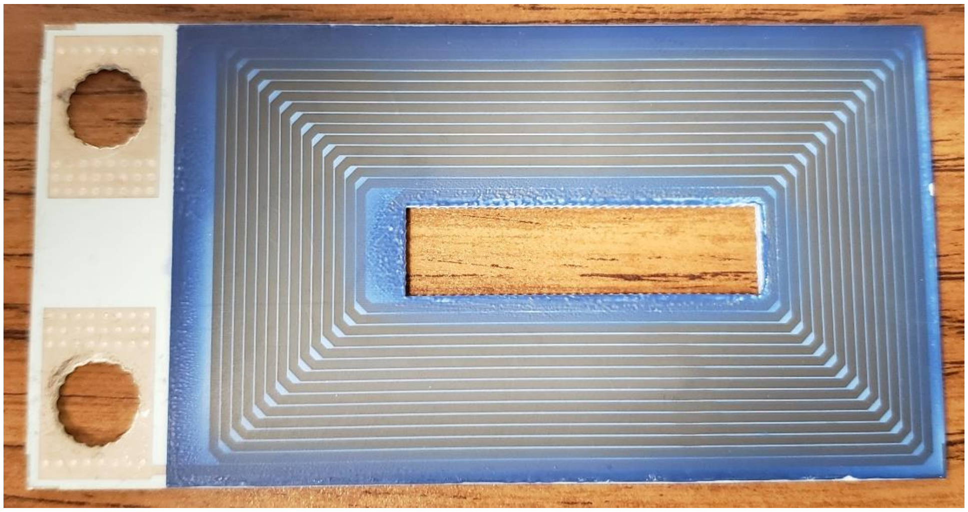

Fig. 24(b) LTCC secondary winding. [Image by author]

Resistances of the LTCC planar transformer windings when compared to those of the PCB planar transformer, are higher. The reason is because there is less number of winding conductor on the LTCC planar transformer compared to those on the PCB planar transformer. In the primary winding of the LTCC planar transformer, there are only the top and bottom winding conductors because vias are used to connect them internally. The assembly of the LTCC transformer is a little tricky when compared to the PCB as there has to be some sort of physical connection between the layers in order to establish the connection. So a thin copper foil is placed in between the layers and they are all connected by screws and nuts which establishes connection throughout the layer. Fig. 25 shows the image of the transformer assembled. The core is taped using an insulation tape to provide isolation as well as to make sure that the core does not move when operating.

Fig. 25 Assembly of LTCC transformer. [Image by author]

4.5 Impedance analysis

A Bode Analyzer was used in order to determine the impedance and inductance characteristics with respect to the frequency. In order to setup the analyzer, calibration has to be done for open circuit, short circuit and load with 50Ω impedance. Once that calibration is done we can connect those pins to the primary side of the transformer in order to run the analyzer and get the results. This was done for both planar and LTCC based transformer.

The impedance vs frequency Bode plot is shown in Fig. 26 for the planar transformer. From the plot, it can be seen that the cut-off frequency is a little below 100kHz. In order to operate the transformer effectively, we have to stop the flow of in-rush current. This can be done only when the impedance is increased. In order to increase the impedance, we have to operate the transformer only in higher frequencies. If we try and operate it at low frequencies, the impedance will be almost negligible which will increase the losses drastically.

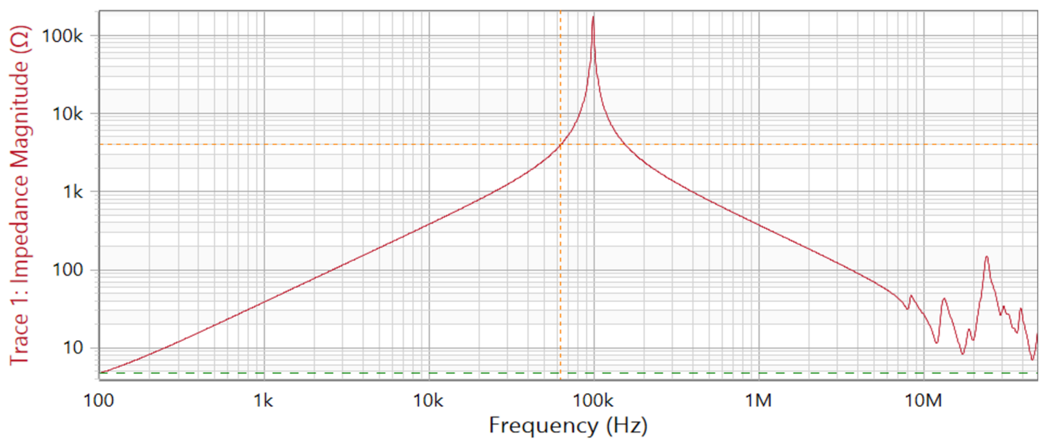

Fig. 26 Impedance vs frequency plot from bode analyzer. [Image by author]

Fig. 27 shows the inductance vs frequency for the same. From these plots, it can be seen that the ideal operating frequency would be around 60kHz and at that frequency, inductance is almost 10mH. If we calculate 2*π*60kHz*10mH, the impedance value is around 3.77kΩ which can be verified in the plot.

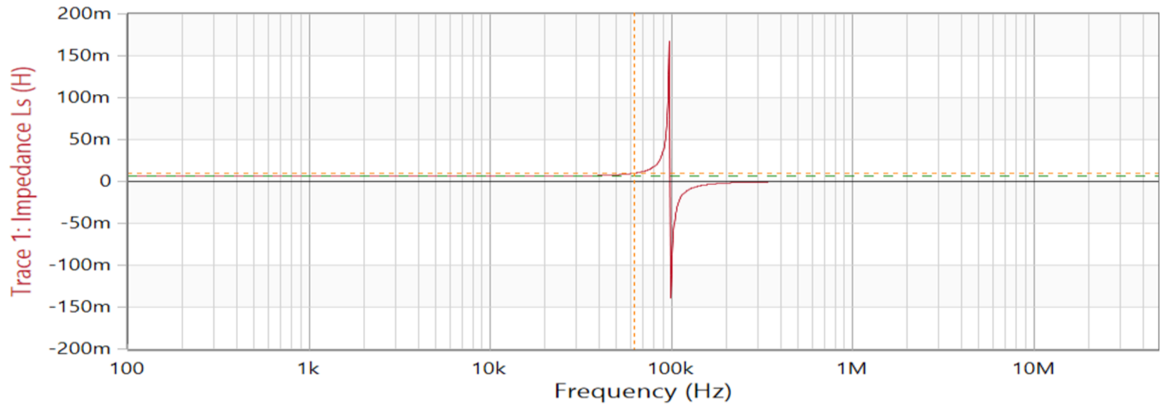

Fig. 27 Inductance vs frequency plot from the bode analyzer. [Image by author]

Impedance analysis was performed for the LTCC based transformer as well. Fig. 28 shows the setup for impedance analysis of LTCC based transformer.

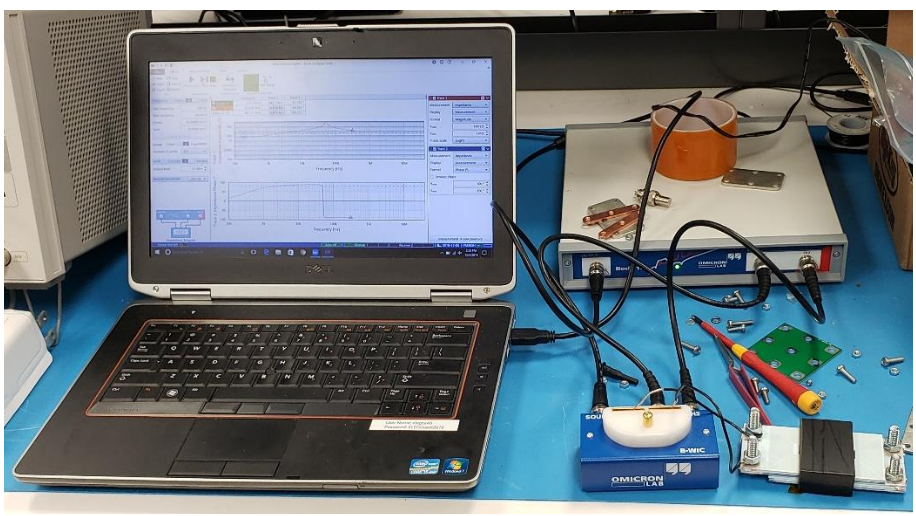

Fig. 28. Impedance analysis test setup. [Image by author]

Based on the characterization, cut-off frequency was found to be around 51kHz. The impedance increases along with the increase in frequency and inductance based on the equation 2πfl. The ideal operating frequency would be 10kHz for which the inductance is 21mH which is shown in Fig. 30. If we calculate the impedance using these values, it comes around 1.352kΩ. This can be verified from the plot in Fig. 29.

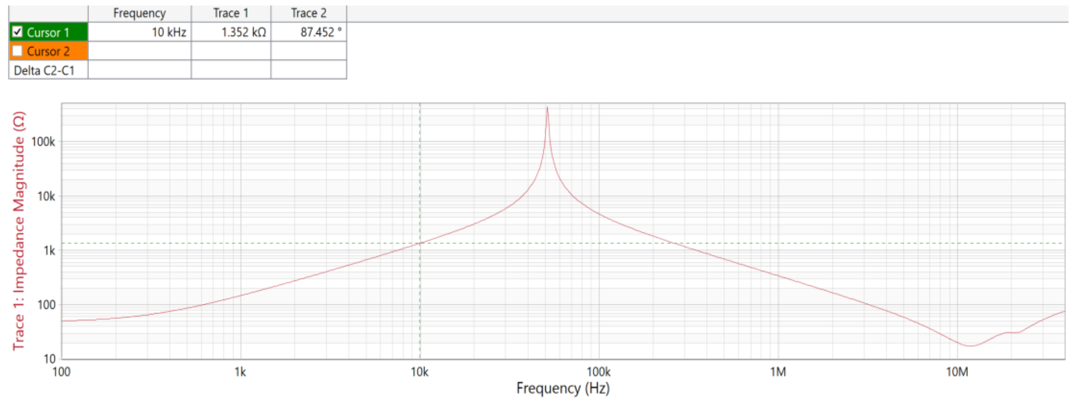

Fig. 29. Impedance vs frequency plot of LTCC based transformer. [Image by author]

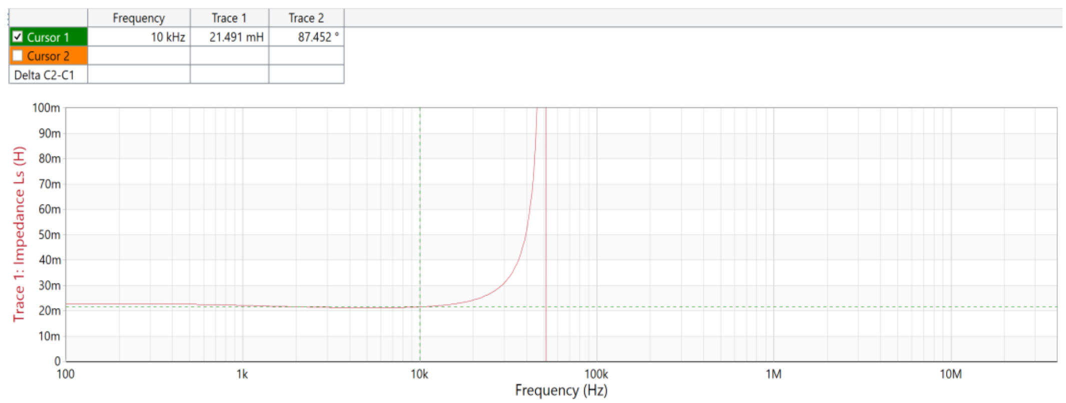

Fig. 30. Inductance vs frequency plot of LTCC based transformer. [Image by author]

When comparing both the materials, that is PCB and ceramic, consider the frequency 10 kHz. At 10kHz, for PCB, it can be seen that the impedance is around 400Ω and for ceramic it is 1.352kΩ. Also the inductance at 10kHz for ceramic is around 21.49mH whereas for PCB it is only around 10mH. From this comparison, we can conclude that, higher the frequency, higher the value of impedance is for ceramic. If the impedance value is higher, it means that the in-rush current will be low and as we increase the primary voltage, there will be better flux linkage with the secondary.

In terms of design, ceramic is designed with less conductive material than that of PCB so that it reduces the capacitive effect of the transformer. If the capacitance is low, at high frequency, the impedance will be higher based on the relation $1/2\pi fc$.

Chapter 5. Conclusion

5.1 Summary

This work mainly focuses on the planar magnetic transformer. The transformer design methodology and fabrication processes are explained in detail. General design procedure, fabrication steps, and the main challenges when working with the planar transformer are discussed. There are some losses that constitute to the degradation in performance of the transformer. The temperature increases rapidly when operated to around 200°C which is very high for the PCB to handle. That is the reason why we moved to the ceramic version.

In the ceramic version of the transformer, design changes were made according to LTCC design rules. Fabrication was done in the clean room and all the steps are explained in detailed. Once the fabrication is done, electrical characterization such as impedance analysis was done on both the transformers. The results are shown in the form of Bode plots to compare the impedance characteristics of planar and LTCC based transformer. From these comparisons, it is safe to say that LTCC based transformer will operate more efficiently than planar transformer at high frequencies.

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