Low Profile Transformers Using Low Temperature Co-Fire Magnetic Tape

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ABSTRACT

There is a growing need for transformers that are low cost, small, low profile and surface mountable. In addition they must meet safety requirements while maintaining transformer efficiency. This paper discusses an approach geared to meet these requirements. It involves parallel LTCC processing of ferrite tape and low temperature (850-950°C) co-firing of the screen printed silver primary and secondary coils resulting in a small low profile highly reliable product.

INTRODUCTION

The current trend in IC manufacturing is to lower the cost by integrating more of what used to be external circuitry into the IC chip. Even so there are still a large number of passive components needed to support these ICs. For example, the modern computer modem has been reduced to two ICs plus about 125 passive components. Among the largest of these parts are high dielectric breakdown transformers. Although transformers have been decreasing in size over the years as power requirements decrease and operating frequency increases, the basic wire wound technology/construction has not changed substantially since Michael Faraday's discovery in 1831.

Currently the need for size reduction is being addressed through the use of small wire wound toroidal cores. Hand winding is required for the very small toroidal cores in which there is the greatest interest. The fact that fabrication by automated means is precluded because of their size and shape has a negative impact on their cost. This paper will discuss an approach to transformer manufacturing (LTCC) that involves an interconnected stack of planar inductors. In this scheme wire winding is not required. The current carrying inductive elements and connecting conductors are screen printed on ferrite sheets which are stacked and formed into a monolithic body. Size reduction is achieved because the inductors are buried in a magnetic matrix, while the low cost requirement is realized via the parallel processing methods associated with LTCC. [1]

LTCC TECHNOLOGY

The LTCC ferrite tape sheets that form the magnetic matrix are generally 2 to 15 mils thick. They are prepared from a slurry of magnetic powder, thermoplastic resin, solvent and surfactants. The slurry is cast on a polymer carrier film moving under a doctor blade, the height of which determines the tape thickness. The required thickness uniformity is achieved by optimizing the slurry properties and the tape casting parameters (speed, temperature and airflow). Heaters in the casting equipment expedite the removal of the solvent converting the cast slurry into a flexible ceramic tape.

LTCC TRANSFORMERS - DESIGN CONSIDERATIONS

The design of transformers in LTCC ferrite tape presents several challenges to the traditional ways of thinking and designing transformers. First, the windings are embedded in the ferrite tape. This is like winding with magnetically shielded wire. A transformer functions because the magnetic flux lines created by one winding cross or link to another winding. If you bury the wire coil in magnetically conduc-

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tive material, the flux will concentrate near the wire and not reach out and link with other turns or windings. Magnetic flux, like people, always seeks the easiest path.

Another difference is that the ferrite tape now becomes the insulator between the windings. If dielectric breakdown between windings is a concern, as it is in most transformers that provide galvanic isolation, the ferrite material must have high resistivity. This requires the use of NiZn ferrite. Unfortunately, NiZn ferrite does not have a high permeability and is limited to a permeability of about 2000. The main design concerns for LTCC transformers are contamination of the ferrite by the other materials used in the construction of the transformer reducing the ferrites resistivity and spacing of the windings and conductors within the transformer. There are several different ways to create and position the coil turns. As is always the case in life, each involves trade offs; to gain performance of one parameter means decreasing the performance of another parameter. The design challenge is to prioritize the requirements and work within the constraints.

Another concern is the parasitic effects of the windings. Capacitance due to the high aspect ratio of the windings width to thickness and the fact they are stacked on top of each other in successive layers will limit high frequency response. Leakage inductance, another parasitic, will be higher because of poor flux coupling causing an overshoot on pulse waveforms and lower power transfer efficiency.

Low winding resistance is important in order to achieve the desired properties and higher power transfer efficiency. This need argues for designs that use high conductivity metals of large cross sectional areas. Silver, copper and gold provide the highest conductivity. Gold's cost generally rules it out. The required inert atmosphere firing for copper raises its manufacturing cost, makes the vehicle burnout more difficult and can adversely affect the properties of the ferrite, so it is rarely used. Silver is the usual choice for LTCC applications. The designer is, however, limited in the conductor cross sectional area that may be used. Large cross sectional areas can cause warping and cracks.

One of the fundamental aspects to deal with is the non-traditional magnetic flux paths. In a traditional transformer the magnetic path is well defined by the core shape, its size and cross sectional area. The windings are well defined and completely separate from the core. Normally the windings are formed on a coil former or bobbin and then the core is placed around them. With LTCC ferrite tape the windings and core are fully integrated. In the traditional transformer, the air, insulation and windings around the coil have much higher reluctance to the flux than the core; hence the flux concentrates in the core. This core magnetic path encompasses the entire winding thus aiding in effective coupling. According to Faraday's law, the voltage induced in a loop or loops of wire (coil turns) is related to the amount of flux passing through the interior of the loop. The flux is directed to pass through the turns by the core; the center leg of an E-core for example. In the LTCC transformer the core is intimate with the windings and thus a low reluctance path is available right next to the wire. Since flux will seek the path of least reluctance, it is not directed to necessarily pass through the other turns of the winding. Flux that does not couple by passing through the other winding turns is lost and referred to as leakage inductance. The questions become, 'How much flux is lost?' and 'Can anything be done to change this?'

This problem has been solved by adding a lower permeability material between the windings on the layers of ferrite tape in order to help direct the magnetic flux to increase coupling as revealed in US patent 6,198,374. This introduction of lower permeability material (that is, lower than the surrounding tape) helps direct and control the flux paths around the coil

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so that more of the flux passes through the winding loops. Figure 1 shows a layer within a transformer with and without this lower permeability material.

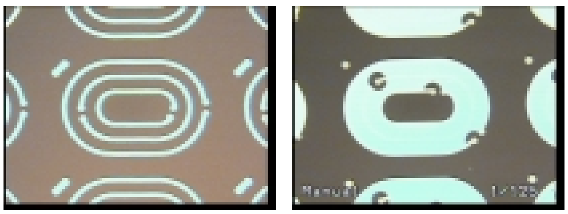


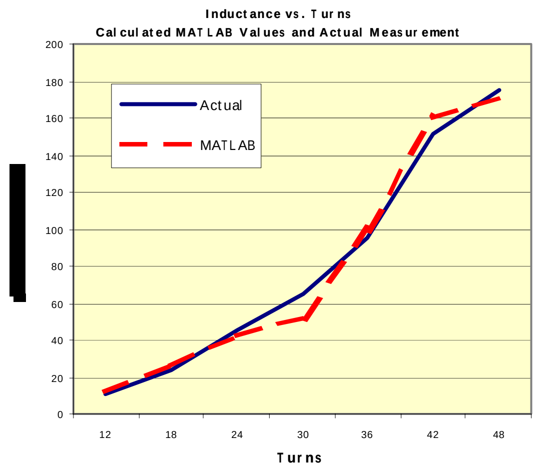
Figure 1

Another design consideration is the amount of area used for the interconnection of the various conductor paths on many different layers to each other in order to form the windings and to gain access to them. These interconnections can consume a large portion of the area available. Since minimum size and cost are key considerations any way to reduce these is beneficial.

A design, which effectively copes with this problem, is revealed in US patent 6,054,914. It discusses locating the interconnection vias in the center core area of the transformer. This allows better efficiency of the available area without adversely affecting the final performance of the transformer.

One approach to determining the results of the unconventional flux paths is by calculating the reluctance of all the possible paths within the structure, including around each conductor in the windings. This can become complicated quite quickly when allowance is made for various different permeabilities within each flux path. The defined paths can be arranged in a matrix form and then solved. This matrix mathematics is best done with a program such as MATLAB which is designed to do matrix math. If done carefully, this method yields representative results for inductance, coupling and leakage once the program has been set up. Figure 2 illustrates a comparison of calculated and actual results for inductance vs. turns.

Figure 2



A more intuitive approach is to use finite element modeling software like Ansoft's Maxwell. Here the geometry of the structure can be inputted as well as the properties of all the materials used. Our work has found this method's inductance calculations to be representative of the actual test results. This tool also provides pictorial maps of flux density and other properties allow one to see where and what the flux patterns look like.

MATERIALS DEVELOPMENT

The LTCC transformer required the development of a materials system that could be fired at low temperatures and result in dense, flat, crack-free parts. Compatible magnetic tapes, dielectric pastes, conductors and via fill pastes were needed. NiZn ferrite was chosen as the magnetic material because of its high resistivity and relative ease in processing.[2] The highest permeability of this material is generally obtained when it is fired at temperatures >1000°C. Silver based materials were chosen for the conductor and via fill. This choice was made not only to meet the need for low cost and high conductivity, but also because of its ability to lower the firing temperature and facilitate grain growth in the ferrite.[3] However, the use of silver does limit one to firing temperatures of

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Table 1

Designation	Material	Form	Function	Resistivity
40010	NiZn ferrite	LTCC tape	Magnetic matrix	108-1011 W
4926-JH	Dielectric	TF paste	Redirect flux & increase BDV	1012 W
903-CT-1A	Silver conductor	TF paste	Form & connect buried inductors	3 mW/sq
902-CT	Silver conductor	TF paste	Via fill	4 mW/sq

about 950°C as silver melts at 960°C. The choice of material for the dielectric was based on the need for compatibility with the ferrite tape and the conductors, its contribution in raising the BDV, its effectiveness in providing the needed reluctance and its ability to achieve these functions after being co-fired with the other materials. Permeability and Q are also affected by the dielectric composition selected.[4] Testing of a variety of materials resulted in the material choices listed in Table 1.

A portion of a fired transformer is shown in Figure 3. Note that the ferrite has fired into a monolithic body containing the silver traces and vias and dielectric films. No delamination, or cracking is evident after co-firing. All of the dark area is dielectric, some of which pulled out during sample preparation.

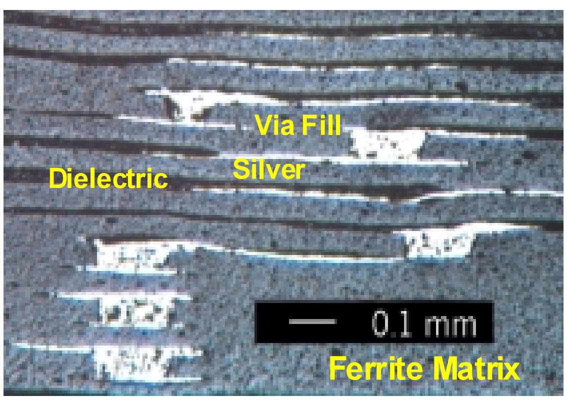

Figure 3

The firing conditions affect the properties of the ferrite matrix as shown in figures 4-7. Figure 4 shows the effect of temperature profile on permeability. Although higher permeabilities can be obtained at higher temperatures, the use of silver for cost considerations limits the values obtainable. Permeability is optimized when the grain structure is large and uniform.[5] Figure 5(a-d) shows the relationship between grain structure and permeability. Breakdown voltage also varies with firing conditions. Figure 6 shows the effect of peak firing temperature on the breakdown voltage

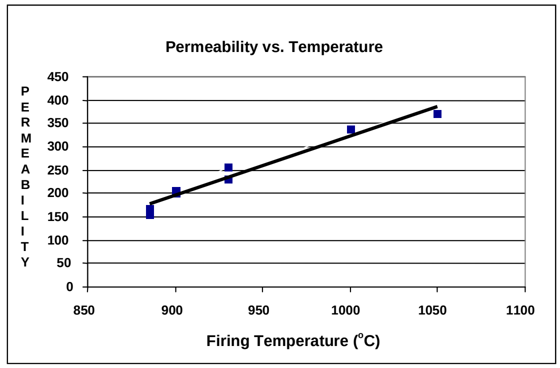

Figure 4

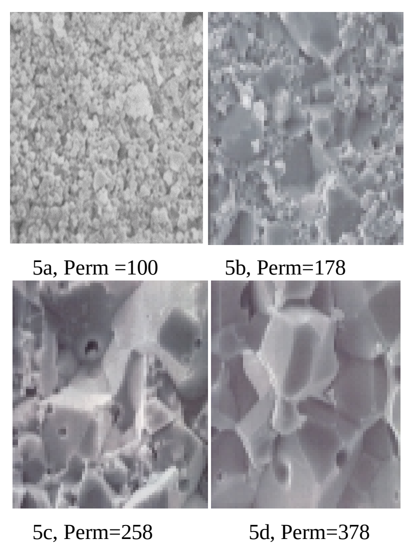

Figure 5

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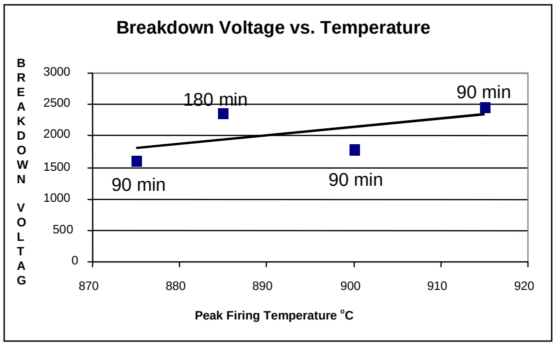


Figure 6

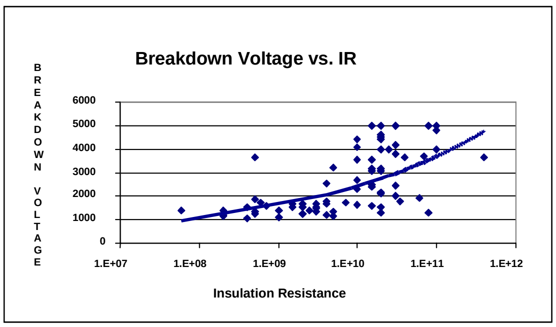


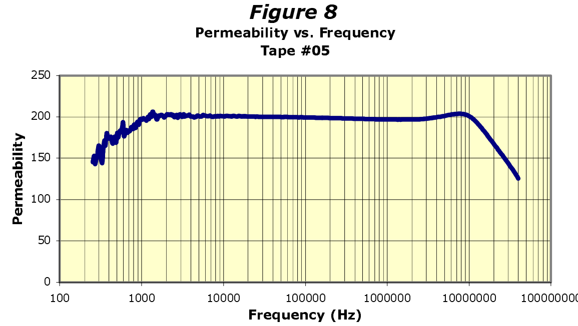
Figure 7

of interdigitated lines separated by 0.010" and covered with dielectric paste. There is also a relationship between insulation resistance and breakdown voltage. This is shown in Figure 7.

IMPLEMENTATION

Numerous transformers have been designed and built to test the limits of materials and layout. One transformer has been developed to meet the requirements of digitally interfaced telecom analog modems. This transformer can provide low power and clock signals across a 1500Vac barrier and is designed to meet the requirements of IEC 60950 for dielectric breakdown. Its low profile (less than 0.60"), small size (0.2" x 0.3") and cost effective manufacturing compare favorably against traditional hand wound toroidal transformers mounted in plastic headers used for the same application. The robust structure is easily manipulated by SMT equipment and there is no fear of broken wires due to shipping or handling. A series of demonstration transformers for low power switching applications in the 250kHz to 2MHz frequency range have also been built. These include turns ratios from 1:1 to 1:4, all with split primary and secondary windings, allowing for series, parallel or center tapped connections. The transformers can also be used as inductors, including use with limited DC bias. The high coupling in these designs comes from the trade off of a lower dielectric breakdown. Table 2 lists some of the basic transformer parameters.

Figure 8



Important material characteristics for the transformers are illustrated in the Figures 8 through 10.

Table 2

Part No.	Turns Ratio	Pri Res.W	Sec Res.W	Pri Ind.mH	Sec Ind.mH	Leakage Ind.	CouplingK (2)
		± 20%(1-4)	± 20%(5-8)	± 20%(1-4)	± 20%(5-8)	mH	
95006	1:1	0.75	0.75	19.0	19.0	2.6	0.93
95007	1:1.5	0.75	2.15	20.0	47.5	2.2	0.94
95008 (1)	1:2	0.75	1.35	15.0	57.5	1.6	0.95
95009	1:2	0.75	3.65	20.0	82.0	1.9	0.95
95010	1:2.5	0.75	3.00	16.0	98.5	1.6	0.95
95011	1:3	0.75	4.30	16.0	145.0	1.5	0.95
95012	1:3.5	0.75	5.65	17.0	210.0	1.4	0.96
95013	1:4	0.75	7.10	17.0	270.0	1.4	0.96

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Figure 9

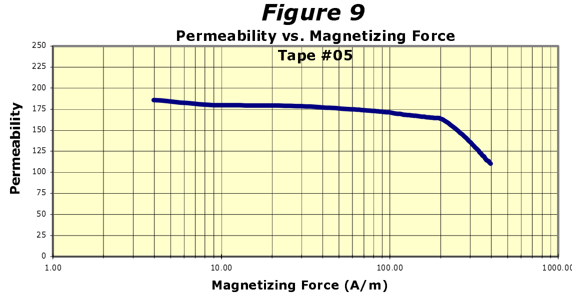
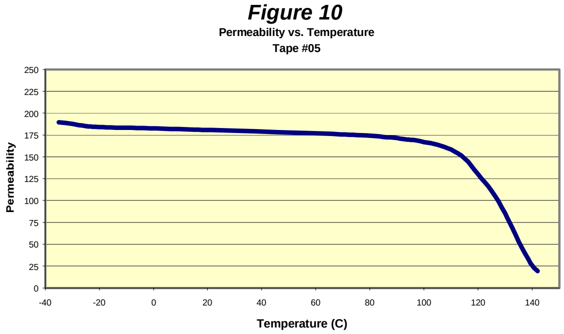


Figure 10



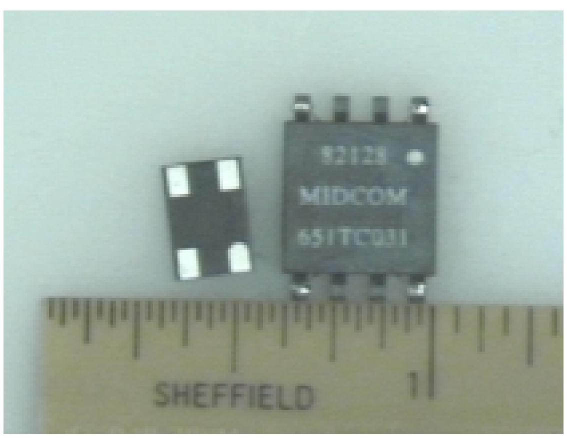


Figure 11

CONCLUSION

In this paper we've discussed some the opportunities and challenges of building LTCC ferrite transformers. A low profile transformer has been built that meets the requirements for digitally interfaced telecom analog modems. Another series of transformers meets the requirements for low power transfers with galvanic isolation. Though many challenges still lay ahead commercially viable transformers exist today. Figure 11 compares a new transformer with the wire wound version it is replacing. The next phase will be to incorporate additional passive components such as capacitors and resistors with the transformers to create even more space saving and cost effective solutions for today's electronic industry.

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