Designing and Building Microwave Circuits in LTCC

Prakash Bhartia & Akshay Mathur
Natel Engineering Co., Inc. Chatsworth, CA 91311 USA

Deepukumar Nair, Jim Parisi, Ken Souders
DuPont Electronics and Communications, TW Alexander Drive, RTP, NC 27519

Abstract

This paper provides a short review of Low Temperature Co-fired Ceramic (LTCC) in the design and development of Microwave and RF Circuits. The review is not intended to be comprehensive, but rather to provide information to capture the interest of current designers who have not been exposed to this substrate technology. The potential advantages and disadvantages of LTCC for microwave applications are discussed, together with characteristics of this medium and design rules.

Introduction

Low Temperature Co-fired Ceramic (LTCC) is an extension of thick film multi-layer technology that has the versatility to be used to design and build microwave and RF components and subsystems. While the technology was used almost exclusively to build military circuits in the past, it is now used extensively for low cost microwave components such as filters, switches, couplers, amplifiers etc. Of greater interest is the use of LTCC to develop three dimensional circuit structures, as resistors, capacitors, inductors, filters, couplers and other passive microwave elements can be built into the different layers and active die etc. incorporated on the surface by epoxy die attach and wire bonding. This article provides a short review of what LTCC is, what the ranges and limitations are with respect to circuit components and how this differs from regular FR-4 or regular thick film technology such as alumina etc. The literature in LTCC is extensive and is therefore impossible to cover in every aspect. A quick internet search will provide the reader with much more detail on the use of LTCC for not only microwave and RF circuits, but also for other applications such as sensors, antennas, actuators, micro-systems, etc.

What is LTCC?

A number of companies such as DuPont, Ferro, Hereaus and Kyocera offer their own LTCC systems. The system consists of a tape together with conductor, dielectric, resistor inks and pastes. The tapes are available in their green (un-fired) state, either as sheets or in a roll and consist of alumina and glass particles held together by an organic binding material on a Mylar backing. The LTCC fabrication process is shown in *Figure 1*.

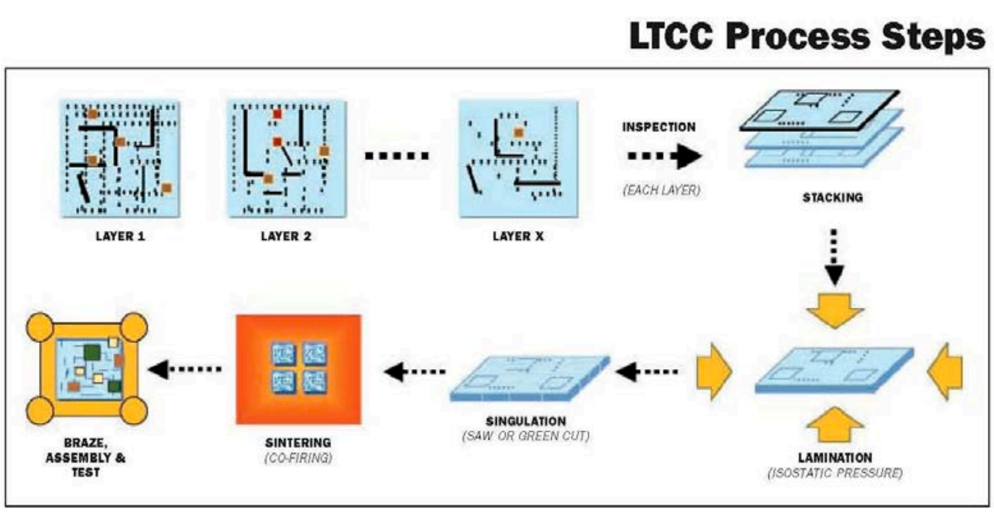

Figure 1: LTCC Process Steps

First, the roll or sheets are cut to the appropriate size and mounted on a frame. While frames offer their own advantages, frameless processing is also used. This is called “Blanking”. Vias are now punched into the sheets and the holes metallized to form electrical interconnects between the different layers. The desired resistors, conductors, thermistors, dielectric pastes are then patterned on each layer as required to form the passive components and then the different layers aligned and laminated under moderate pressure and temperature.

At this point, the ceramic sheets are co-fired or sintered together with the conductors and then the circuits separated. The “Low Temperature” aspect of LTCC comes from the fact that the firing temperature is about 900° C which is much lower than the 1800° C temperatures used for HTCC. The “co-fired” in LTCC comes from the fact that all the layers are co-fired simultaneously rather than in thick film where each layer has to be fired separately. Naturally this results in cost savings. The tapes normally come in 5 or 10 mil thickness and the principal characteristics of interest from a microwave RF point of view are shown in *Table 1*.

	DuPont 951-AX	**Ferro A6-S**	**DuPont 9K7**	**Heraeus CT 2000**
Dielectric Constant	7.8	5.9 ± 0.15	7.1 ± 0.2	9.1 ± 0.1
Green thickness (μm) Fired thickness (μm)	254 205	127 99	127 105	99 77
Tan δ	0.0055 (>1 GHz)	0.001 (>1 GHz)	0.001 (>1 GHz)	0.0027 (>1GHz)
Insulation Resistance	> 10^{12}Ωcm (100 VDC)	> 10^{14}Ωcm (bulk resistivity)	> 10^{12}Ωcm	> 10^{13}Ωcm (bulk resistivity)
Breakdown Voltage	>1000V/25μm	>5000V/93μm	>1100V/25μm	>1000V/25μm
Color	blue	white	blue	white
Thermal Conductivity	3 W/mK	2 W/mK	4.6 W/mK	3W/mK
Thermal Expansion	5.8 ppm/K (25...300)°C	7 ppm/K (25...300)°C	4.4 ppm/K (25...300)°C	8.5 ppm/K (25...300)°
Shrinkage: z-axis x-, y-axis	(15 ± 0.5)% (12.7 ± 0.2)%	27% (15.5± 0.2)%	(11.8 ± 0.3)% (9.1 ± 0.3)%	14% 11.5%

Table 1: LTCC Material Data

Of significance are the relatively high dielectric constant, low loss tangent and stability of the dielectric constant over a broad based frequency range. Below, we discuss some of the features such as line widths, spacing, via sizes, resistors, inductors, capacitors and cavities in LTCC, as these are the basic building blocks of any circuit. Nominal values are discussed, to provide the designer a guideline. Hence, for high volume production, it is preferable to provide greater flexibility while for R&D purposes tighter specifications can be achieved. For example, line widths should be greater than 10 mil for high volume production, about 6 mils for normal designs and can be less than 5 mil for R&D purposes.

Before going into these details, the designer should be cautioned about tape shrinkage when fired. The shrinkage is predictable and the conductor, resistor dielectric pastes etc. are designed to work with this. Newer “no shrink” tapes are now available. However, it should be noted that while most of the x-y shrinkage has been eliminated, the z-direction shrinkage is still present. Finally, while circuits with up to 70 layers have been built, 5 – 30 layers circuits are more common.

Materials

While *Table 1* provides the characteristics of the tape, depending on the process system chosen, one needs to use the specially constituted gold, wirebond, brazing, via fill, resistor (both co-fired/post fired) dielectric materials. These are outlined in *Table 2*. This choice is highly dependant on the electrical circuit requirement, together with the physical and environmental condition requirements. In addition, cost is also a major factor.

Manufacturer	**DuPont**		**Ferro**
Process	**951**	**9K7**	**A6-M/S**
Inner Layer Au	5734 TC502 (export control)	LL505	30-025
Via Fill Au	5738 TC501 (export control)	LL502	30-078
Wirebond Co-Fire Au	5742 (AI wire) 5734 (Au wire) TC502 (export control)	LL507 (1 & 2 mil Au wire) LL505 (1 mil Au wire, transition to bond ledge)	30-065 (AI wire) 30-025 (Au wire)
Wirebond Post-Fire Au	5771 (Al and Au wire)	5771 (Al and Au wire)	30-068 (AI wire)
Solderable Au	5739 (Pt/Au)	LL509 (PtAu)	36-020 (Pt/Au)
Photoimageable Au	5989		4002
Brazing Material (AUSn, AuGe Braze)	5062D/5063D	5062D/5063D	4007
Inner Layer Ag	6142D (Signal) 6148 (Power, Grid)	LL612 (Signal) LL602 (Power, Grid)	33-398
Via Fill Ag	6141 (Ag) 6138 (Pd/Ag)	LL601 (Ag) LL701 (Au/Ag)	33-343 (Ag) 39-005 (Pd/Ag)
Solderable Co-Fired Ag	6146 (Pd/Ag)	LL627 (Pd/Ag)	33-391
Solderable Post-Fired Ag	6135 (Pd/Ag)	LF171 (AgPt)	3350
Co-Fired Resistors	CF Series	Ag System HFB12, 20 Ω/square HFB22, 200 Ω/square Au System E114065-108, 25 Ω/square E114065-109, 100 Ω/square E114065-123, 1000 Ω/square	87 Series
Post-Fired Resistors	2000 Series (Ag) 1900 Series (Au)		82 Series
Co-Fired Dielectric	9615R	9615R	10-088
Post-Fired Overglaze	9615R	9615R	NCAa
Photo Imageable Dielectric			NCAa

Table 2: Material Options

Line Widths and Spacing

Typical line widths and spacing should be about 6 mils or more. In addition, the spacing between the via pad edge and any line should also satisfy this criteria to avoid potential shorting problems. Conductors and ground planes should be designed to have a spacing of > 10 mil to the conductor or substrate/cavity edge to avoid shorting during substrate mounting.

Laser ablation for fine lines and spacing

DuPont has recently developed a laser ablation technique using a UV laser to achieve very high tolerance patterning process on LTCC. The laser process can realize 1 mil (25.4 um) line width and spacing compared to typical 4-5 mil achieved by standard screen printing techniques. The laser process is a non-contact process and highly repeatable. It is also compatible with LTCC tape when it is in green state as well as after firing. The process capability enhancement brought about with the laser process makes it possible for the first time to realize passive components with unique characteristics. It also enable direct flip chip attachment of MMIC's with bump pitches smaller than 6 mil (150 um). In addition to fabricating narrow lines the laser process can also be used to drill very small (~2 mil diameter) vias when the tape is in green sheet form.

Vias

Vias in LTCC serve multiple purposes. They can be electrical or thermal in nature. For electrical vias, while smaller vias are possible, generally 10 mil vias are common. The separation distance between adjacent vias should be about 3 via diameters and where many vias are required they should be staggered to avoid substrate cracking. A stagger pattern or zigzag pattern in the multiple layers is preferred. In microwave and RF circuits, one may need to place the vias parallel to the controlled lines throughout the shielded cross sectional area to provide high frequency and impedance controlled lines with buried coaxial shielding.

The other type of via is a thermal via required for heat conduction and cooling. Again, these are similar in size to the electrical vias and can be arranged in an array for maximum effect. The typical maximum size is about 250 mil square. Selecting a via diameter that permits the maximum packing density under the component of interest achieves the best thermal impedance reduction. In addition, the thermal impedance can be reduced significantly by stacking thermal vias.

Resistors

Resistors can be either buried or of the surface type. Resistor inks are available from the manufacturers for both types. For surface resistors inks with values 10 Ω/sq to 1 M Ω/sq are available, while for buried resistors typical values are 10 Ω/sq to 10 K Ω/sq. For resistors that have to be measured or trimmed, the preferred size is 15 mil sq. While surface resistors can be trimmed to higher tolerance levels (1 – 2%) buried resistors typically have a ± 20% tolerance. In addition, one must allow for conductor terminations as large as 30 mil on each end and they can be built as an array. Depending on the fabrication house, other criteria such as distance from cavity or substrate edge etc. will also have to be satisfied. Buried resistors can be trimmed by laser through a special hole in the upper foil.

Capacitors

Capacitors can be fabricated easily by placing parallel plates on adjacent tape layers. Using just the tape itself, values up to 450 pf / in^2 are possible, but using other dielectric materials, values to 45 nf/ in^2 have been demonstrated. The largest size should not exceed 50% of the substrate cross section. With other common dielectrics eg.X7R – capacitors up to 3000 pf, ± 20% and NP0 – 200 pf, ± 10% are common. Typical capacitors are interdigital, electrodes on both sides of a tape, vias filled with high permittivity material etc.

Inductors

Spiral and helix type inductor configurations are available in a wide range based on use of the standard LTCC tapes or ferrite tape material. LTCC inductors can be realized in the range of 5 nH to about 200 nH depending on the type of inductors.

Cavities

One of the good features of LTCC is the ability to have cavities. These are introduced in the structure in its green state, prior to firing and must obey certain design rules regarding size, via to cavity wall clearance, bond shelf distances etc. These design rules vary from fabricator to fabricator but are readily available. Besides the normal role that cavities can be used for in microwave circuits, they are useful in LTCC for embedding active components on the substrate surface, thereby minimizing module height and enabling short and controlled impedance wire bonds and also to reduce the thermal impedance of high powered components.

Microwave Components and Subsystems in LTCC

While many of the features cited above are similar to what can be achieved with multi-layer circuit boards using laminate materials such as FR4, LTCC does offer a number of unique advantages. These include:

- High conductivity metals – resulting in lower loss
- Low loss and better controlled dielectric properties
- Embedding passive components, resulting in smaller size and increased functionality
- High reliability, suitable for producing low cost modules
- Low density, lighter weight solution
- 3-D structures, allowing smaller size and footprint
- Brazed pins, seal rings, connectors and heat sinks, thereby increasing functionality and reliability and decreasing costs
- Co-firing the layers reduces cost and production time
- Each layer can be inspected prior to stacking
- Many microwave passive components such as filters, baluns, couplers are easily realized

Not withstanding the above advantages, the technology is gradually being improved upon and RF data for the passive components and the materials are not readily available. In addition, tape shrinkage remains a concern, although now zero shrink tapes are available. From *Table 1* it is evident that LTCC dielectric materials with low loss, comparable to Alumina are now available. With the relatively low firing temperature of LTCC, high conductivity metals such as gold and silver can be used in the metallization layer resulting in excellent microwave and RF low loss circuits.
As is evident, the structure is ideal for microstrip and stripline and coplanar waveguide circuits. The RF bias control interconnects and passive elements can all be integrated in a single substrate. High RF isolation can easily be obtained with placement of ground planes, and RF shielding structures are easily integrated, avoiding the need to machine RF isolation walls. The elimination of machined internal walls reduces complexity resulting in good cost savings.

What results from this procedure is a robust compact design that can be mass produced at low cost. While most circuits require a package for the substrate to be mounted in, a ring frame is easily brazed on the substrate and can be sealed by a lid thereby eliminating the expense of a package.

Many software packages are available for the design of microwave circuits in LTCC. For example, Ansoft Designer from Ansoft allows the design of the active and passive modules such as switches, front-ends, amplifiers etc. easily on LTCC. This package combines Ansoft's High Frequency Structure Simulator (HFSS) for 3D structures with system, circuit and planar EM simulation. Embedded passive components can be modeled as done for printed circuit boards using EM simulation, HFSS, Planar EM or Spicelink 3D to extract electrical performance. HFSS a full-wave 3D solver, can be used for high frequency and complex geometrics and can perform package analysis. These simulator tools allow for accurate designs and can be worked with thermal and stress simulation tools simultaneously to ensure power handling capability before circuit fabrication.

While LTCC is a very attractive option for microwave circuits, some issues need to be considered. We have already discussed the issue of tape shrinkage. In addition, potential resonant structures must be eliminated by careful layout of RF ground planes, bias components and control connections. Pocket cut-outs surrounded by ground vias will result in resonant cavities. RF losses, though controlled by use of highly conductive metals, can be high if the metallization pattern results in high surface roughness and poor edge definition, due to skin effect losses. Ideally all interconnect transmission lines should be minimized. Some mechanical issues such as substrate surface flatness, metal loading within the substrate to facilitate uniform shrinkage during firing etc. also need to be addressed to ensure a robust design.

Some of the other challenges include the lack of appropriate RF characterization models. Parasitic coupling is often significant and reliable tools to predict both wanted and unwanted coupling are required.

Many companies in the US, Europe and Asia offer full LTCC design and fabrication capability. Scrantom Engineering, a Natel company, offers a full range of services for products up to 60 GHz, supported by an in house design center. The designer can choose any of the systems offered by DuPont, Ferro, Heraeus or others. A conceptual example of an LTCC substrate is shown in *Figure 2* while *Figure 3* shows some typical finished substrates.

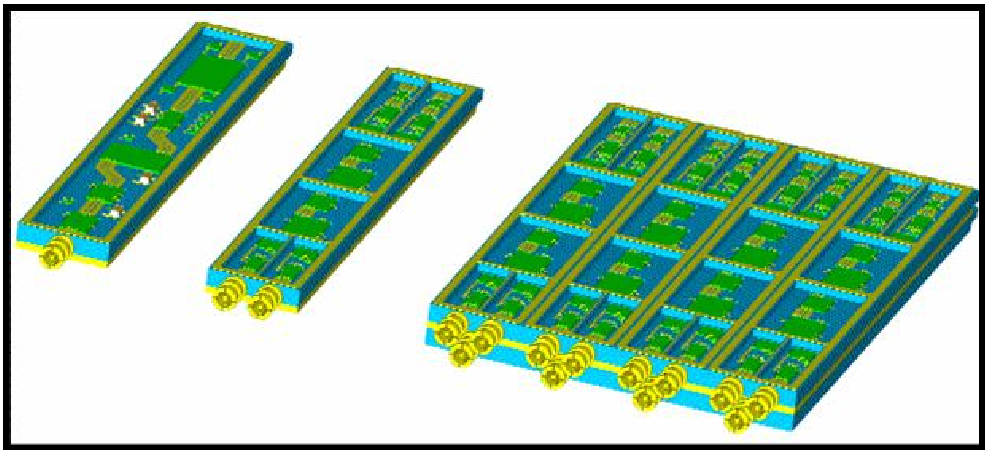

Figure 2 – Tx/Rx Modules

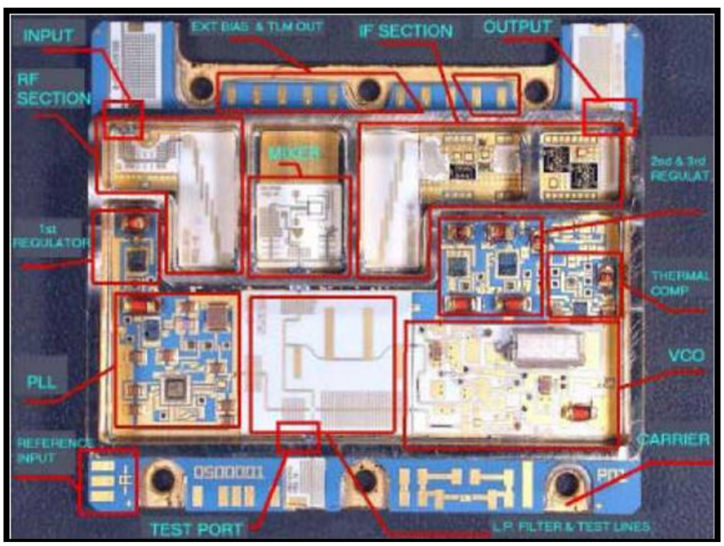

Figure 3- System in a Package (SIP)

The technology has been used extensively for wireless applications such as base station modules, transmitters and receivers, power splitters and combiners, mixers, filters, amplifiers, matching networks, in other applications such as T/R modules for radar systems, GPS, sensors etc., and in the automotive industry for engine management systems, adaptive cruise control and alarm systems, anti-lock braking systems, ignition and sensor modules etc. The reader is referred to the internet websites of many companies that offer these products which can be found by a simple search.

Silver metalized LTCC and thick film

Use of silver or mixed silver / gold metallization for high reliability applications has been limited due to concerns related to silver migration, Kirkendall voiding, and silver tarnishing. Silver is the metal most susceptible to migration, since it is anodically very soluble and requires a low activation energy to initiate the migration process. Silver under humidity and applied electric field tends to migrate and may reduce isolation gaps and may ultimately cause electrical shorts.

In spite of the above mentioned issues use of silver in multilayer ceramics (LTCC and thick film) has been growing primarily to drive costs down and in some cases improve RF performance. Natel EMS has spend considerable resources to develop processes that minimize possibility of silver migration by assuring hermetic encapsulation of silver in inner layers and electroless Ni/Pd/Au plating on exposed silver metallization. Platable metallizations offer a unique solution to historical reliability concerns with silver LTCC in electronics systems. This process has been in commercial use for last four years and has undergone rigorous environmental testing to prove equivalence to all-gold packages. Natel's process has demonstrated compliance to temperature cycling under humidity and DC bias (MIL STD 810E, method 2003.8), salt atmosphere (MIL STD 883, method 1009), moisture resistance (MIL STD 883, method 1004), in addition to the usual qualification requirements of Mil 883.

Natel's mixed metal process also offers significant improvements from the traditional mixed metal system that is highly susceptible to Kirkendall voiding. Natel process eliminates the use of transition via fill materials that provide insufficient prevention from void formation due to limited compatibility with gold metallization. Silver diffusion rates are typically 3 to 4 times greater than that of gold at LTCC firing temperature. Voiding occurs due to silver depletion. Natel's unique proprietary process eliminates the possibility of differential diffusion between silver and gold thus eliminating possibility of void formation.

Conclusion

This paper has presented a short review of LTCC technology and its advantages over thick film and for the fabrication of microwave and RF components. While the technology is useful for microwave and RF products, it is also invaluable for military, sensor and products for other industries such as the automotive industry.