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Design aspects of microwave components with LTCC technique

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Abstract

Low temperature co-fired ceramic (LTCC) technology, widely used in the automotive industry, is now being employed in microwave applications. Several commercial materials with low dielectric losses at microwave frequencies and adequate thermomechanical properties have been introduced. Computer-aided design of three-dimensional circuits has also become available. These advances together with high-quality manufacturing technology have placed LTCCs at the forefront in the development of miniature microwave devices. The paper outlines LTCC technology placing emphasis on those essentials of the materials and processing technologies about which the microwave circuit designer needs to be aware. The discussion is illustrated by examples.The crucial issue of component reliability is also addressed. Although the integration of passive components into the structure improves reliability, the joints between the LTCC module and PCB remain as significant 'weak link'. Therefore, thermomechanical and structural design is a key to reliable LTCC assemblies.Finally, some future trends the LTCC technology for microwave applications are outlined.

Keywords: Design; Interconnects; LTCC; Microwave ceramics

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1. Introduction

The ever widening range of microwave products in the consumer electronics market is continuously pushing device and component manufacturers to seek new advanced integration, packaging and interconnection technologies, as size, cost and performance are critical factors for the success of a microwave product. Traditionally, high-performance microwave modules are machined from metal and co-axial connections are provided with RF connectors, which generally result in expensive, heavy and bulky packages.[1,2] These metal packages cannot meet the market demand for portable, high-volume and low-cost modules with multiple external I/Os.

One of the most promising integration technologies is the multilayer low temperature co-fired ceramic technology (LTCC). In this technology, passive components, such as inductors, capacitors and filters, are integrated into multilayer LTCC substrate. Bare MMICs (Monolithic Microwave ICs) and other discrete components are mounted onto the surface of the LTCC substrate and sealed. The benefits of LTCC technology, such as the parallel manufacturing process with high yield and low cost, the ability to utilise highly conductive and inexpensive metallization, quick rounds in prototyping, environmental stability, compact structures, integration, etc., are well known.[3–5] Recently, many papers have reported about high-performance LTCC microwave modules up to 76 GHz.[6,7] Although there are also other high-density, multilayer substrate technologies available, such as organic laminates, LTCC has a unique set of combined characteristics, which makes it a more attractive alternative as the frequencies shift into the microwave region.

The target of this paper is to address the special issues that should be considered when designing LTCC components for microwave applications. 'LTCC component' here means a whole assembly, as shown in Fig. 1. Special attention is paid to the selection of LTCC materials, to the LTCC process demands and to the electrical function of multilayer components. External interconnections, reliability and sealing are also discussed.

2. Design aspects

The LTCC design aspects of microwave applications are illustrated in this work with electromagnetic (EM)

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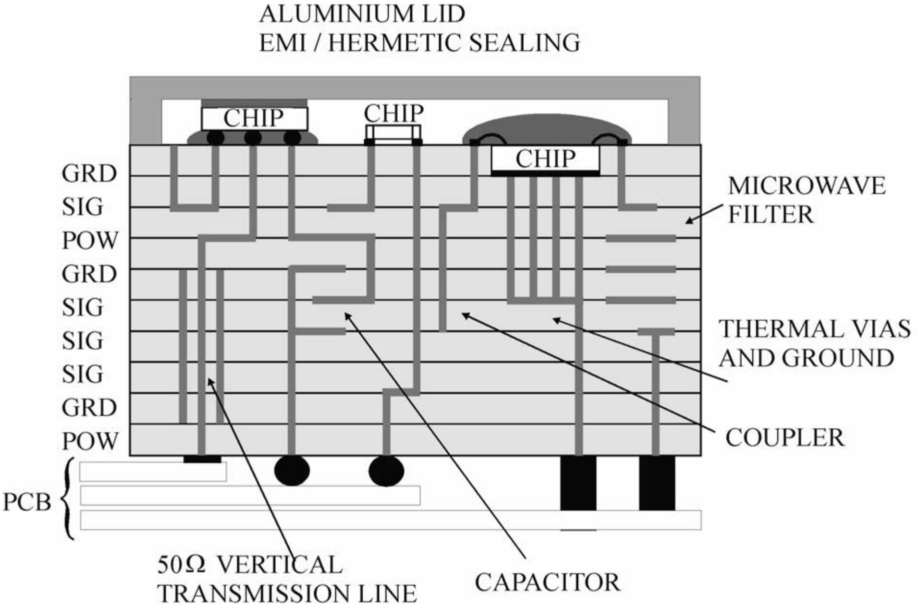

Fig. 1. Schematic illustration of a LTCC assembly including embedded passives, external interconnections and sealing.

modelling and 'in-house' experiments. The EM models with Sonnet and empirical measurements, if not mentioned otherwise, were done for a balance $\lambda/4$ strip line resonator with a resonance frequency of 5.2 GHz due to wireless HiperLAN applications. Permittivity was 7.5, fired thickness 750 μm and strip line width 1 mm.

2.1. Material selection

In the development of LTCC applications, several material properties need to be taken into account. The electrical properties of the dielectric and conductor materials are the basic issue, but designers should also be aware of the effects of the thermomechanical properties, production costs and variation range of each parameter. In Table 1, some typical properties of commercial LTCC materials from data sheets are listed and compared with alumina and FR-4. More detailed descriptions of material properties can be found in the corresponding material data sheets of the manufacturers or several publications.[8, 9]

Permittivity, total loss and temperature dependence are the most important electrical properties in material selection, especially for high-frequency applications. These attributes enable the construction of, for example, microwave filters with convenient size and impedance matching, low insertion loss, steep cut-off of the performance curve and operational stability against ambient temperature change.[10,11]

As shown in Table 1, the relative permittivity values, ε_r, of commercial LTCCs, which are commonly measured at low frequencies, are in the range of 3–10, where the values for alumina and FR-4 also fall. However, LTCC compositions with much higher permittivity values ($\varepsilon_r > 20$) have been developed, to enable miniaturised, embedded capacitors, inductors, filters and antennas.[12,13] The permittivities of commercial LTCCs are very stable, and lot to lot variations are generally $< \pm 0.15$ ($\pm 2\%$). Moreover, the frequency dependencies of permittivities are very low, e.g., for DuPont 943 ε_r changes from 7.6 at 1 GHz to 7.48 at 12 GHz

Table 1
Physical properties of commercial LTCC materials, alumina and FR4

Property	Commercial LTCCs	96% Al_2O_3/ Coors	FR-4
Permittivity, commonly at 1 MHz	3.9…9.1±0.1…±0.15	9.2	5.5
Loss Tangent, commonly at 1 MHz/%	0.07…0.6	0.3	2
Mwave Insertion Loss/dB/m at 10 GHz	4.7…23.6		
TCE/ppm/K	4.5…7.5	7.1	12–16
Thermal conductivity/ W/mK	2…4.5	21.0	0.2
Young's modulus/ GPa	80…150	314	24
Flexural strength/MPa	116…320	397	430
Surface roughness/ μm/in	<1…25	<25	
Green tape thickness tolerance/%	±2…±9		
X,Y-shrinkage/%	9.5…15.0±0.3		
Z-shrinkage/%	10.3…25.0±0.5		
Metallizations	Au/Ag		Cu

(1.6%)[3] compared with change more than 10% over the frequency range 1 kHz to 1 GHz for FR-4.[14] These two sources of variation together may cause deviation between the designed and measured frequency performances. According to our EM simulations, a permittivity deviation of ±0.1 achieves a ±38 MHz (±0.7%) resonance frequency deviation for a 5.2 GHz resonator. Thus, for more accurate permittivity, values should be established to encourage the utilisation of LTCC technology especially at microwave frequencies.

The prediction of the exact insertion loss of a microwave component is more complicated. The main losses in the frequency range from 4 to 44 GHz are conductor losses, but the relative importance of dielectric and roughness losses increases as a function of frequency.[15] Thus, in LTCC multilayer structures, high conductive metallisations are an important benefit. The square resistances of recommended silver pastes are about 2...3.5 mΩ^2 with a fired line thickness of 10–15 µm. Much lower dielectric losses of LTCC than FR-4 at microwave and millimeter frequencies also result in lower loss signal connections and higher Q values.[3,13] Recent material development has produced new-generation LTCC systems (e.g. DuPont 943) with insertion loss values comparable to alumina substrates, which can easily satisfy the normal electrical specifications of high-frequency applications.[8,16,17] The dielectric loss still depends on frequency, and we have measured for one commercial LTCC an increase of 20% from 1 MHz to 8 GHz. Thus, the lack of accurate data makes the prediction of high-frequency performance difficult and, with critical specification, this has to be measured empirically.

The temperature dependence of the resonance frequency, τ_f, is an issue rarely discussed with LTCC components. However, the τ_f value of 10 ppm K^{-1} causes a 0.11% shift of resonance frequency (5.5 MHz at 5.2 GHz) within the temperature range of −30 °C...+80 °C. Large τ_f values are especially problematic, because temperature compensation requires additional mechanical structures or electrical circuits.[18,19] Recently, novel LTCC materials with nearly zero τ_f values have been developed (e.g. Heraeus CT2000, τ_f < ±10 ppm K^{-1}).[5,12,20] Even in this case, the component designer must be aware that the structure itself may affect its τ_f. Fig. 2 shows our τ_f measurements for balanced $\lambda/2$ strip line resonators made of Heraeus CT2000. Although τ_f is basically a native property of each ceramic material predetermined by its microstructural phases,[20] Fig. 2 demonstrates that the designed structure also affects temperature stability. For other LTCC materials, higher τ_f values have been reported,[20,21] and designers may find this parameter quite problematic, as it necessitates extra measurements and causes uncertainty in the material selection. However, the τ_f values of novel LTCCs are much better than those for FR-4 (+80 ppm K^{-1}).

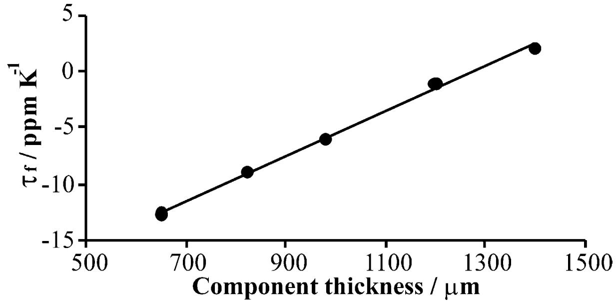

Fig. 2. Effect of the thickness of a balanced strip line resonator on the temperature dependence of the resonance frequency.

The final important material aspect of microwave modules is its thermomechanical properties. They include many properties that affect the reliability of the designed components. A specific requirement comes from the coefficient of thermal expansion (CTE), which should be chosen to match closely the value of the mounting board and chip. This means that if the LTCC module is mounted on silicon, CTE should be about 4 ppm K^{-1}, while on alumina it should be 7–9 ppm K^{-1} and on PCB 12–20 ppm K^{-1}.[22–24] The thermal conductivity of LTCC is another important aspect that will be discussed later. Furthermore, LTCCs must meet a number of mechanical requirements, such as high fracture strength and Young's modulus and low surface roughness (for high-quality printing). Table 1 shows that LTCCs are mechanically weak compared with alumina and, in some cases, to FR-4, but their CTE values make them quite compatible with silicon chips. Novel LTCC materials with tailored thermomechanical properties, such as Kyocera HITCE are also available.

2.2. Process demands

In the LTCC fabrication process, green ceramic tapes are mechanically punched to form holes, or vias, followed by stencil and screen printing processes, whereby vias are filled and patterns generated. Ceramic sheets are then stacked, laminated and sintered followed by post-firing metallisation, electrical testing, final assembly and shielding. Table 2 shows the basic design rules common for LTCC modules as well as the process variation to be taken into account. More detailed information can be found at the manufacturers' websites. The individual process-to-process variations are large, but only those especially important for microwave applications are discussed here; via density and the fine line technique, meshed ground planes and the positioning accuracy of different LTCC layers.

As the operational frequency increases, more vias are needed to provide isolation between the different elements. If, in demanding applications, the appropriate via density cannot be achieved by the punching technique, several LTCC component manufacturers offer

Table 2
Common design parameters for LTCC multilayers

Design parameter	Values
Minimum width of conductor lines and spaces	150 μm
Tolerances of widthness of conductor line and spaces	±20 μm
Layer to layer positioning accuracy after firing	60 μm
Minimum diameter of vias after firing	150 μm
Minimum spaces of vias	300 μm
Typical diameter of thermal vias	200–450 μm
Ground plane coverage ratio	50%
Number of layers	10–24

the preparation of vias with laser. Thus, via density does not limit the utilisation of the LTCC process at microwave frequencies. High-frequency applications also emphasize the need for an accurate and repeatable preparation method for narrow embedded conductor lines and line spaces.[25] Several methods especially suitable for LTCC tapes enabling line widths <100 μm have been developed.[26,27] These methods with small, accurate vias can make the LTCC technology an even more competitive choice for microwave applications.

Large conductor areas, such as grounds, are not allowed in LTCC structures, because they may cause component warping during the co-firing process.[28] This forces designers to use meshed ground planes with metallization coverage below 50%, causing excess decrease of the *Q*-factor of resonators and degraded isolation properties. Our earlier experiments have shown that meshed ground planes with coverage as high as 55% decreased the resonance frequency of a 2 GHz balanced strip line resonator by about 17 MHz from the values available for uniform ground planes.[20] Simulations for identical resonators operating at 5.2 GHz showed an even larger decrease of the resonance frequency (32 MHz). Thus, with an increasing operating frequency, the component designer must be aware of the effects of meshed ground planes and avoid them by using subsequent double ground layers or extra vias.

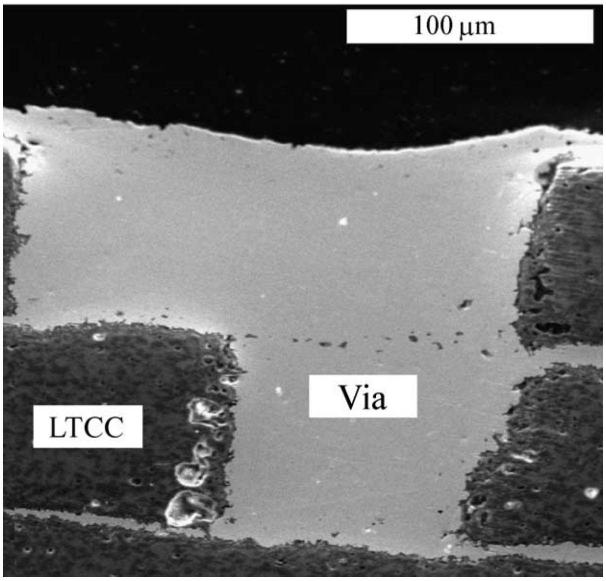

Fig. 3. Cross-section image of vias in a LTCC module with an optical positioning system for layer stacking.

Proper positioning of the conductor vias and patterns of subsequent layers is very crucial in the LTCC process, where the positioning accuracy depends on the sizes of the discrete structures inside the module. Usually, the stacking of different layers is done mechanically, i.e. tapes are stacked with pins in punched registration holes. The achieved accuracy is about 60 μm, which is not enough for high-frequency applications, where the required dimensions of discrete features are small and the number of vias large. In these cases, more accurate optical position systems are used. The 'in-house' system uses optical positioning employed throughout the process, including via preparation, printing and stacking (Fig. 3).

2.3. Electrical design

The design procedure has been well reported for embedded capacitors, inductors, resonators and transmission lines. Once the materials and processes to be used have been selected, the actual design of a microwave application can be started by using a circuit simulator (like Aplac) to estimate the required elements. Then, the actual three-dimensional layout can be modelled with electromagnetic simulators (Sonnet, Empire, Ansoft). By taking into account the high-frequency properties of the materials and the limitations of the process parameters, the designer may only need a few prototyping rounds.[29]

As the operating frequencies increase, the wavelength of the electrical signal approaches the physical size of the different elements, such as package cavity, substrate traces and external interconnects. At the same time, higher integration levels force one to consider the various coupling effects in more detail. Therefore, the three-dimensional distributed effects of all these elements must be well controlled and modelled. Usually, a low insertion loss (<0.5 dB) and a high return loss (>15 dB) per board level connection are required as well as low reflection between the transmission lines, vias and MMIC and good isolation between the circuit elements.[1,30]

The LTCC technology offers the component designer a number of effective methods for ironing out detrimental package resonances, to improve the isolation between the circuit elements and to provide constant impedance lines in the horizontal and vertical direction. The capability to add component cavities, layers and vias without a significant increase of cost is undoubtedly one of the key benefits of LTCC modules at high frequencies. Inexpensive metal-filled via holes can be effectively used to isolate the high-radiation areas of the module. Vias can be placed in critical regions, such as around chip cavities and between neighbouring transmission lines, to eliminate possible cavity resonances and to decrease coupling between lines.[31,32]

A multilayer LTCC provides a variety of transmission line structures. The precise control of dielectric thickness and the excellent stability of electrical properties ensure that the electrical characteristics of the transmission lines are well predictable. A strip line offers negligible dispersion and radiation and the upper and lower ground planes provide shielding and may be used as a reference plane for other lines. Interconnection to, for example, MMICs generally requires a microstrip or a coplanar waveguide well studied earlier.[32–35] It is highly recommended that all of the reference planes (power/ground) of the same type are connected at many points by vias. In this way, power/ground inductance can be minimised inside the module, the possible power delivery resonances are moved towards higher frequencies and switching noise is reduced.

For some high-frequency applications, very low permittivity materials ($\varepsilon_r < 4$) are especially useful. As can been seen in Fig. 4, lower ε_r enables the designer to use thinner strip line structures for 50 Ω impedance designs, with decreased total height of the package. It also allows reduction of package-induced noise levels, since signal lines can be closer to the ground/power planes, reducing the coupling noise between adjacent signal lines.[36] The dimensions can also be reduced by using fine-line techniques.

2.4. Off-substrate interconnects, protection and reliability

The off-substrate interconnections can be divided into two categories; chip-to-substrate and substrate-to-PC board connections.

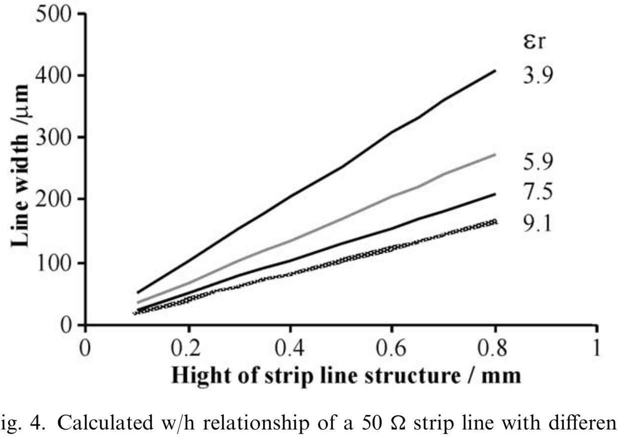

Fig. 4. Calculated w/h relationship of a 50 Ω strip line with different commercially available ε_r values for LTCC materials.

There are two *chip-to-substrate interconnection* technologies currently available for LTCC; wire bonding and flip chip bonding (Fig. 1). Wire bonding is a widely known and well standardised chip level interconnection method, and it is therefore most often utilised for cost sensitive microwave applications.[37] However, above several GHz, the long wire bonds start to cause increasingly high signal losses and crosstalk problems. For a 410 μm long and 17 μm thick wire, the maximum cut-off frequency lies around 15 GHz, using 15 dB return loss as a criterion.[38] To increase the bandwidth of the wire technology up to 40 GHz, ribbon bonding and multiple wires can be used.[39,40] Another alternative is to minimise wire lengths by placing a die into the LTCC cavity structure (Fig. 1). It has been demonstrated that insertion and return losses better than 0.5 and 20 dB, respectively, up to 75 GHz can be achieved with 200 μm long wires and chip-cavity construction.[41]

The flip chip interconnection technology provides very high integration densities and also allows several processing and material variations, e.g. high-temperature solders (Au/Sn, Pb90/Sn10) and thermocompression bonding.[42] Very short solder or gold bumps, normally of the order of 25–100 μm after mounting, effectively reduce parasitic interconnection losses. Optimised bump interconnects have been reported to possess excellent electrical transfer characteristics in the microwave and mm-wave region up to 100 GHz.[43] Bumps are also highly repeatable and predictable in size, which facilitates the package simulations and compensation of interconnects. A noteworthy benefit of LTCC as a chip carrier is that it enables flip chip bonding directly on solid metal vias, which increases the routing flexibility of signal lines and may further improve signal integrity. However, the non-planarity of the LTCC substrate and the line pitch limitation of the standard thick film process may, in some cases, prevent effective utilisation of the flip chip mounting technology.[44,45]

For the *LTCC-to-board* interface, a wide variety of interconnection technologies are available. One of the most promising interconnection technology that creditably fulfils most of the microwave requirements is ball grid array (BGA).[46] BGA balls with diameter of 0.3–0.9 mm are available. Kyocera has recently reported that, by combining the BGA and LTCC technologies, it is possible to obtain a low-cost surface mounting technology compatible package with a wideband capability up to 50 GHz.[47] The utilisation of BGA interconnects with a multilayer LTCC substrate also leads to a small package size and a high interconnection density with a flexible wiring design and improved thermal and electrical management. Especially the reduction in the chip-to-board electrical path and parasitics has a positive impact on the signal-to-noise ratio, and crosstalk noise can be effectively attenuated using extra ground/power pins.

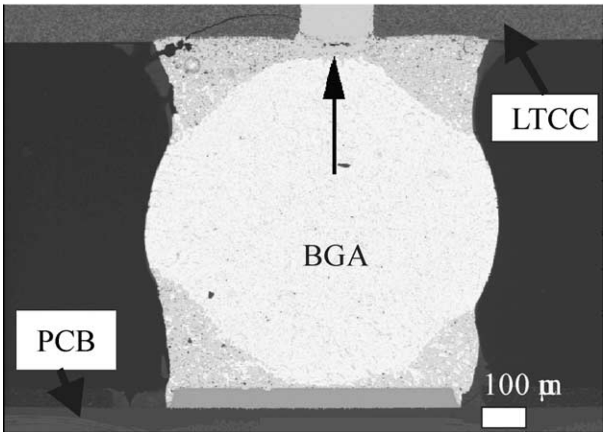

Fig. 5. Cross-section image of a LTCC–BGA–PC board connection after thermal cycling.

To optimise board level *reliability*, several factors must be addressed in BGA type connections. These factors include interconnect height and substrate dimensions and the thermomechanical properties and metallurgic compatibility of interface materials, etc. Also, 'in-house' LTCC/BGA reliability tests have revealed that the substrate design may have a significant effect on the reliability of BGA interconnects. Fig. 5 shows SEM images of typical crack paths in a temperature cycling test −40 to 125 °C in a BGA/via interface.[48]

The reliability of BGA joints can be improved by combining cavities, reducing module size, using underfill or short vias, increasing stand-off height and stiffness and diminishing module thickness, which all affect the microwave performance of the LTCC module.[49–53]

Finally, an increasing amount of consideration must be given to the package thermal design, as higher packaging density and operating frequencies increase power density. One disadvantage of LTCC is its low thermal conductivity, usually of the order of 2–5 W/mK, although it is about 10 times higher than that achieved with organic laminates. In high-power applications, such as microwave amplifier packages, the low thermal conductivity of LTCCs may drastically increase reliability problems. A common method to improve thermal dissipation is to use a heat spreader, but a more advantageous alternative provided by LTCC technology is to place metallic via arrays under high-power components (Fig. 1).[54]

Additionally, the effects of sealing on microwave applications need to be considered. There are several sealing methods (epoxy, frit, and solder sealing) and lid materials (metal, glass, ceramic) available for LTCC substrates, which may also provide sufficient heat removal (Fig. 1). At microwave frequencies, the lid can have a significant detuning effect on MMIC and may induce package-related resonances. Therefore, the possible lid effects must also be well modelled and simulated during the design cycle. In addition, the underfill or glop top materials are known to make an additional contribution to signal integrity.[55,56]

3. Future trends

As indicated in this paper, the following development of LTCC assemblies would be needed for microwave applications:

- Integration of various LTCC layers with high and low permittivities into the same module
- Improved process accuracy
- Higher wiring and via density
- More efficient and accurate modelling softwares
- Novel reliable microwave interconnections
- Integration, for example, ferroelectric layers to proved electrical tuneability

4. Conclusion

LTCC technology is an excellent candidate for large-volume fabrication of microwave applications. This is especially true if materials of the newest generation with low insertion loss, good thermal stability of the resonance frequency and moderate thermomechanical properties are employed.

The survey presented here concerning the utilisation of the LTCC technology for microwave applications has shown that there is no straightforward productive way to design the assemblies. The whole process, including material selection, process demands, electrical design and the use of external interconnects, as well as the reliability issues need to be considered in totality.

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