ANNALS OF THE FACULTY OF ENGINEERING HUNEDOARA
2003, Tome I, Fascicole 3

# RF AND MEMS COMPONENTS IN LTCC TECHNOLOGY

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**Abstract** - *This paper gives the overview of the basic LTCC (low-temperature cofired ceramics) elements: resistors, capacitors and inductors, and their typical integration configurations and applications: RF front-end modules, receivers, transmitters, amplifiers, (PA, LNA) couplers, filters, duplexers, baluns, mixers and antennas. LTCC technology, originally used for packages module, is more often used for construction of new three-dimensional elements like cantilever, bridge, cavities, channels or membranes and simple mechanical sub-assemblies.*

## 1. INTRODUCTION

LTCC is an effective interconnection technology for a wide range of products and has the benefit of providing a three-dimensional structure into which passive RF and MEMS components can be realized as part of the process for fabricating the interconnections within ceramic layers. LTCC technology has found its main use in many modern applications in two main frequency ranges: lower frequency range from 800MHz to 3GHz, and higher frequency range from 3GHz up to 60GHz. Lower frequency applications already exist or they will be available in near future and high frequency range applications still need to spread in practice. The examples of current applications in lower frequency range are mobile phones, pagers, wireless LAN, wireless local loops, Bluetooth, GPS and PCS applications. Higher frequency range applications include earth-to-satellite, satellite-to-earth communications systems, radars in military and avionic applications, collision avoidance systems, see Table 1.

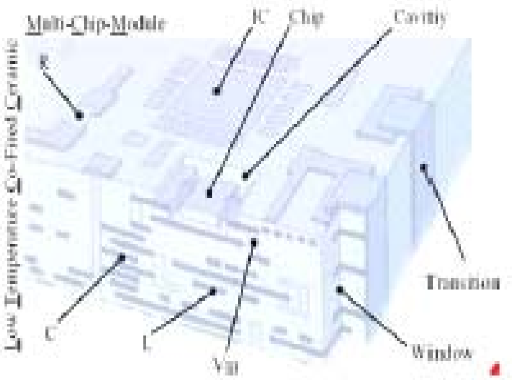
TABLE 1. APPLICATIONS AND THEIR FREQUENCY RANGES [1].

| APPLICATION | FREQUENCY RANGE |
|---|---|
| Mobile phones | 800-900MHz and 1.8-2.4GHz |
| Pagers | 900MHz |
| Wireless LAN | 2.4GHz |
| Wireless local loop | 1.5-3.0GHz |
| Bluetooth | 2.45GHz |
| GPS | 1.2-1.6GHz |
| PCS | 1.8-2.0GHz |
| Earth-satellite-earth | 4-12GHz |
| Radars | 10-40GHz |
| Collision avoidance systems | 35-77GHz |

In the lower frequency range applications, FR4, standard PCB material, has good performance and still prevails as the main PCB medium. However, with the increasing operating frequencies and reduction of the size and mass of electronic devices, it is expected that LTCC materials take over this lead due to its good characteristics. Main advantage of the LTCC, not present in other technologies e.g. in HTCC, is the ability to integrate passive components (resistors, capacitors, inductors) into inner layers of the substrate, leaving the outer surface for active components thus reducing the overall size required. All passive components can be made in one production process, eliminating SMD components, speeding up manufacturing and reducing overall cost of manufacturing. Other advantages include robustness against mechanical stress and temperature, higher dielectric constant values, higher thermal conductivity, lower temperature coefficient of frequency and good integration with semiconductor materials due to similar TCE values.

## 2. BASIC LTCC ELEMENTS

The LTCC materials are comprised of a range of different glass ceramic dielectrics, precious metal conductors and ruthenium oxide resistor formulations. In addition ferrites can be introduced into glass-ceramic dielectric formulations to provide enhanced inductor and transformer properties, and other passive RF components. Basic passive components made in LTCC technology are resistors, capacitors and inductors [2, 3]. Resistors are normally made of ruthenium oxide ($RuO_2$) or tantalum oxide ($Ta_2O_5$). They can have large value range depending on the type of resistive paste used. Tolerances normally achieved are +/-20% when in inside layers, and when on top layer, laser trimming can produce +/-1% tolerances. Capacitors are normally made of silicates or titanates, as parallel plate capacitors with typical values from 1pF to 3nF. However, since 40% of all capacitors in a typical product are greater than 20nF, design challenges lie ahead in developing higher dielectric constant materials and managing the size and number of layers [4]. Inductors are best suited for embedding into substrate layers since typically 80% of all inductors used in handheld products are lower than 200nH [4]. They are normally made of metallic conductors with either spiral or helical shape, in a single layer or over multiple layers. These basic passive components and other active components combined with transmission lines, coupled lines, transitions and vias form more complex structures such as: receivers, amplifiers (power amplifiers, low noise amplifiers), couplers, filters, duplexers, baluns, antennas, mixers, voltage controlled oscillators (VCO), frequency synthesizers etc. An example of a LTCC structure is shown in picture 1.



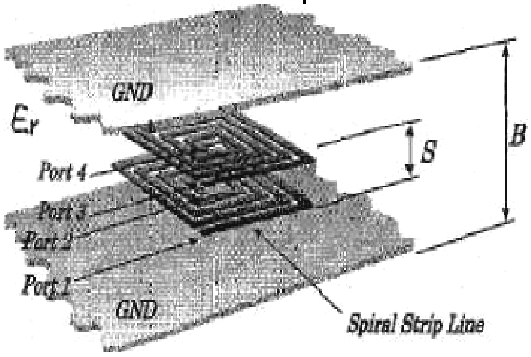
PICTURE 1. LTCC STRUCTURE [5].

## 3. RF COMPLEX STRUCTURES IN LTCC TECHNOLOGY

**Receivers.** RF receivers present a typical application where LTCC technology found its use. Tri-band GSM/PCS/DCS direct conversion receiver was integrated on a LTCC substrate, with PCS balloon, matching elements and SAW filter structures embedded directly in LTCC, achieving receiver sensitivity of -114dBm and noise figure less than 9dB [6]. LTCC features such as cavity formation capability, 3D integration and low loss stripling design made these good characteristics possible. Similarly, a low-power direct conversion receiver for C-band was designed on a LTCC substrate with LTCC front-end filter realized in LTCC completely [7].

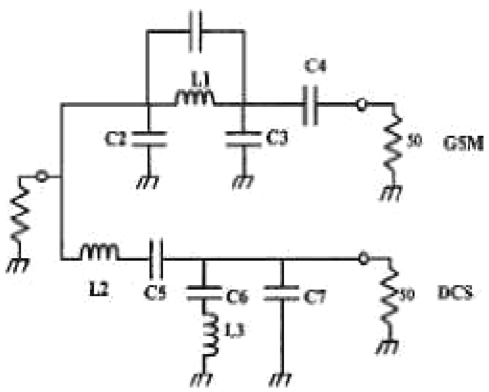
**Amplifiers.** LTCC passives, inductors, capacitors and filters, found its use in amplifier designs due to their high Q values and higher level of integration offered. They are typically used as input and output matching networks for proper termination. 1.9GHz CMOS PA with integrated LTCC passives, power added efficiency (PAE) of 48%, output power of 26dBm, 17dB gain with a 3.3V drain supply voltage was reported [8]. An investigation of CMOS RF power amplifiers with respect to the level of passive integration, (passives-on-chip, LTCC passives and discrete off-chip passives) shows improved output power and efficiency with LTCC solution [9]. High power amplifiers (more than 100Watts) have been demonstrated using LTCC input and output matching networks with challenges stemming from large currents, low impedances, wide RF feed structures and related thermal issues [10, 11]. The use of LTCC technology in LDMOS PA with their low loss transmission lines and formation of thermal vias underneath active semiconductor devices allowed a temperature rise of less than 5°C between active devices and a heatsink [12].

**Couplers.** Directional couplers are necessary parts of wireless equipment, typically used as phase shifters, attenuators, power dividers of local oscillators or power monitors of automatic power control circuits. They have to provide tight amplitude balance, 90° phase difference between direct and coupled ports, as well as small size and low cost. Broadside coupling stripline is a preferred way to realize directional couplers since electrical characteristics can be easily influenced by modification of the distance between stripline electrodes, picture 2.



PICTURE 2. SPIRAL BROADSIDE STRIPLINE COUPLER

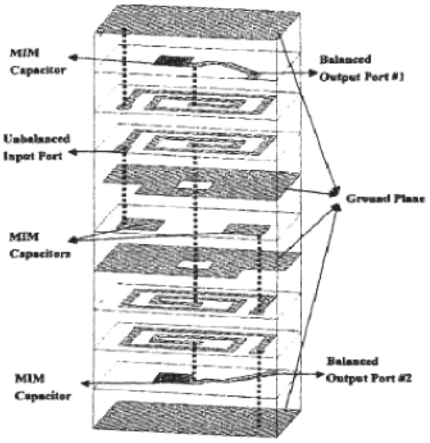
**Filters.** Filters are very important components of modern wireless designs. Bandpass filters are required to separate the uplink (TX) and downlink (RX) transmission paths in wireless systems with a single antenna. Successful implementation in LTCC technology was demonstrated for GSM/DCS/PCS [1], DCS-1800 [13], GSM/DCS [14], AMPS/CDMA [15] and W-CDMA duplexers [16]. The receiver must be well isolated from the transmit path and vice versa, since the receive signal levels are in microwatt and transmit levels in 1 watt range. This translates into low insertion loss requirements for bandpass filters in passing direction with very high suppression in all other bands [15].



PICTURE 3. GSM/DCS DUPLEXER CIRCUIT SCHEMATIC [1].

Narrow-band filters are used for elimination of interference coming from the nearby frequency channel or for image channel rejection [17]. L-band low-pass and high-pass filters were realized in LTCC technology with 25dB of rejection in 1250-1750MHz and 14dB in 3750-5250MHz bands [18]. Rectangular 3D, wide-band ridge waveguide bandpass filters have also been reported, where the vertical walls were realized by arrays of via walls separated by small distance [19].

**Baluns.** Baluns, necessary components for balanced mixers, amplifiers, multipliers and phase shifters, have also benefited from LTCC technology showing excellent characteristics of phase and amplitude balancing. Both semi-lumped baluns and chip-type with stepped impedance method baluns have been realized in practice, picture 4.

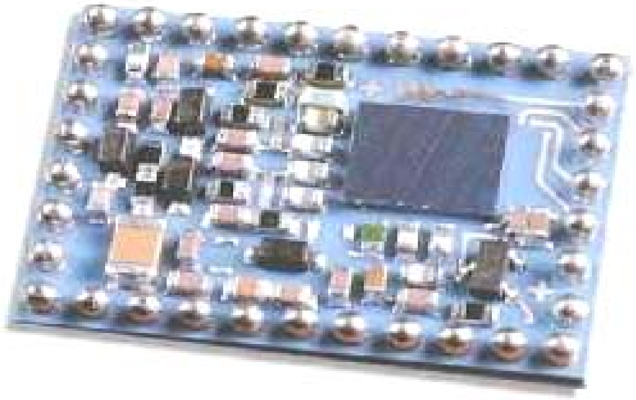


PICTURE 4. SEMI-LUMPED LTCC BALUN

**Antennas.** LTCC process tolerances may affect the performance of RF and microwave circuits in the K- and Ka-frequency bands. In order to increase the sensitivity of the receiver and the efficiency of transmitter power supply, integration of antenna elements with front-end components is necessary [20]. The bandwidth and efficiency of planar antennas are inversely proportional to the value of dielectric constant, which presents one of the major challenges in antenna design in LTCC technology. Reference [20] gives examples of 24.125GHz aperture-coupled patch antenna arrays and [21] shows a 5.8GHz cavity-backed patch antenna. The analysis done in [22] shows that the stacked-patch antennas on LTCC can achieve twice as big bandwidth as that of a single-patch antenna with the same substrate.

## 4. MISCELANEOUS RF MODULES

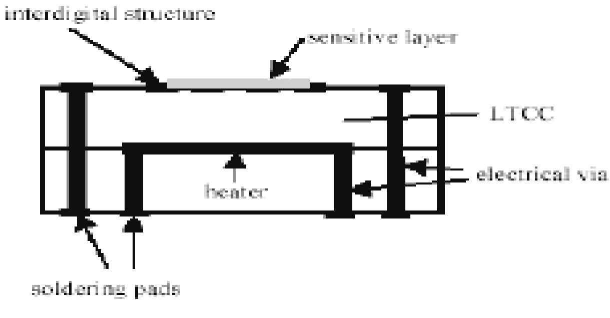
Different RF modules were also realized in LTCC technology, for example, an L-band LTCC mixer with high image rejection [23] and a voltage controlled oscillator (VCO) suitable for 900MHz systems successfully applied in a frequency synthesizer [24]. The LTCC image rejection mixer embedded four balloons, two RF/IF hybrids, one local oscillator signal divider and a HPF in LTCC substrate, achieving 15x13mm2 size. The frequency synthesizer occupied area of 161 mm$^2$, exhibiting low phase noise and fast lock times. Bluetooth is one of the most attractive applications of LTCC technology which offers high degree of integration of embedded passives and makes economic sense as well. It presents a voice and data transmission standard on short distances (10-100m), in the ISM frequency band (2.4-2.5GHz) [25]. LTCC substrates were adopted for Bluetooth modules since they offer 3D integration of interconnections making design smaller. Commercially available Bluetooth modules (Ericsson, PBA 313 1/2, Fig. 5) combine embedded passive components (antenna, miscellaneous filters, VCO tuning, RF switches) with integrated components (RF synthesizer, LNA, power amplifier, VCO and hardware for radio control) in order to obtain optimum performance, size and cost combination.



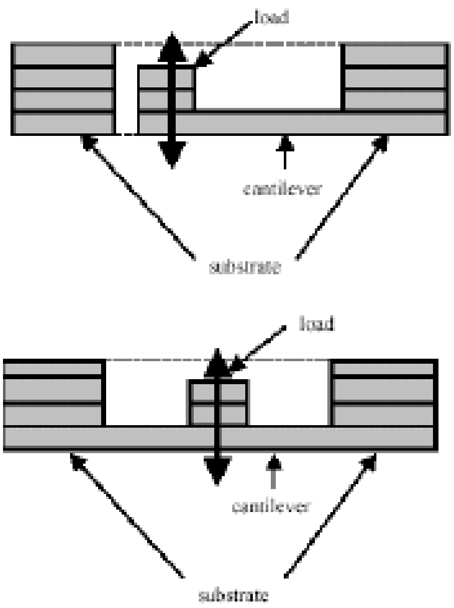
PICTURE 5. BLUETOOTH MODULE PBA 313 1/2 [26].

## 5. MEMS COMPONENTS IN LTCC TECHNOLOGY

The LTCC can be an interesting alternative as base material for microsystems. Microstructures in Si (made with etching and deposition technologies) have smaller sizes than 1 micron, what it is not suitable for all microsystems. LTCC technology offers a possibility to make bigger structure size. These structures are to be found in some kind of mechanical sensors for instance to detect vibrations or accelerations. The bigger size and stability of ceramic cantilever structure enables the use of bigger active masses causing other measurement ranges. Moreover, numerous applications of LTCC devices in biology and chemistry are proposed. Potential of LTCC technology inclines for investigation in the area of these applications. First devices with spatial elements were simple cooling systems and flow sensors [27, 28]. An another sensor application is an indirect heated sensor [29]. It has two separate circuits for heating and for measurement. The described sensor has a thickness of only 200um and consists of two layers of LTCC. The distance between heater and sensor electrodes is as small as only lOOum and enables a fast dynamical behavior of the sensor. Picture 6 shows a cross-section of an indirect heated sensor. LTCC technology offers a possibility to make ceramic cantilever structures or cantilever arrays by using only one or two layers of tape. Thus structure are to be found in same kind of mechanical sensors for instance to detect vibrations or accelerations, see picture 7.

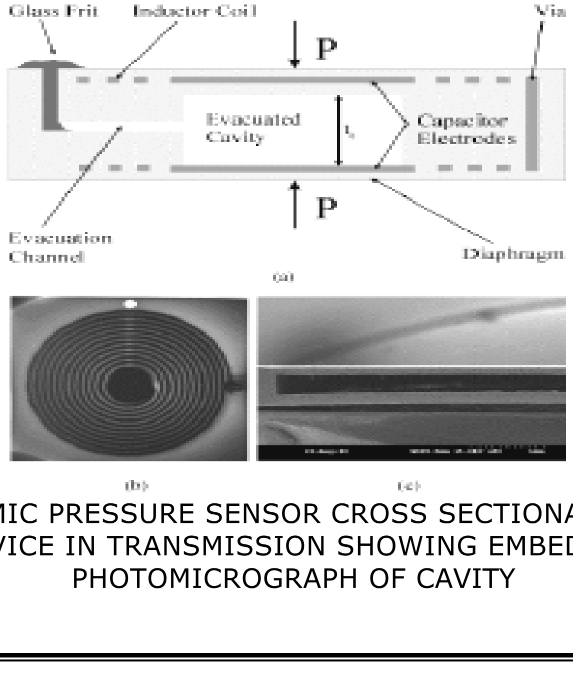


PICTURE 6. INDIRECT HEATED CHEMICAL SENSOR

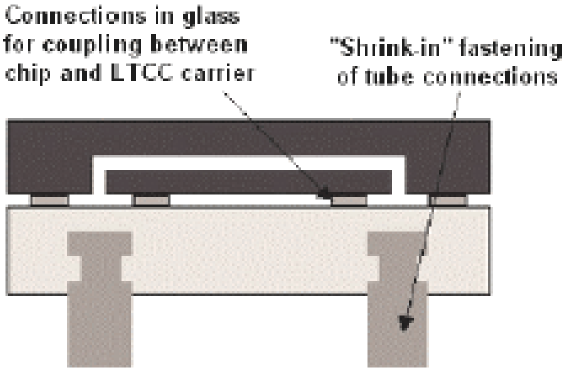


PICTURE 7. ONE-SIDED AND TWO-SIDED FIXED CANTILEVER

There are many applications, such as in turbine and internal combustion engines, in which the sensing of pressure at high temperatures is required. The LTCC sensor (fabricated using multiple sheets of Dupont 951 AT ceramic tape) is based on movable diaphragm ceramic pressure sensors which are read out using passive wireless approaches (operating at 450°C) [30]. The sensor consist of two diaphragms, separated by a vacuum-sealed cavity of gap size $t_g$ (picture 8). If a pressure *P* is applied, the gap size of the cavity between the two membranes is reduced and the capacitor value increases. The capacitor is electrically connected to a planar spiral inductor coil. These components form a passive LC resonator with resonant frequency $f_o$, which is pressure dependent. To achieve passive wireless telemetry, the sensor is placed inside an external loop antenna coil are measured as a function of frequency.



PICTURE 8. (a) CERAMIC PRESSURE SENSOR CROSS SECTIONAL VIEW; (b) TOP VIEW OF FABRICATED DEVICE IN TRANSMISSION SHOWING EMBEDDED COILS; (c) SEM PHOTOMICROGRAPH OF CAVITY



PICTURE 9. TUBE CONNECTIONS TO LTCC

Tube connections to LTCC. One of the main technical problems for industrializing biological and chemical sensor-chips is the connection of liquids and gases to cavities in the sensor. In plain words: there is a lack of "plumbing" methods. LTCC provided with a glass pattern for anodic bonding opens up a complete toolbox for this kind of application. An example is shown in picture 9, below [31].

## 6. CONCLUSION

This paper gave an overview of the RF and MEMS modules developed and implemented in LTCC technology. LTCC technology becomes more and more important, new modules are constantly introduced and for that reason only the most common RF and MEMS modules were presented.

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