LTCC Materials For High Density Multilayer Interconnect

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Abstract

A low temperature cofired ceramic (LTCC) materials containing ceramic fillers and flux was developed with a matched silver conductor paste. These materials are used to fabricate multilayer chip band pass filters for the RF (radio frequency) circuits of the wireless telecommunication systems. The material was sintered at 860°C in 20 minutes to a density of 3.5g/cc. The properties of the densified ceramic are $k = 7.8$, $Q > 500@2.1$GHz, CTE = 4.5 ppm/°C, bending strength ~ 2000 kg/cm$^2$, and $\tau_f = -8.7$ ppm/°C. A multilayer band pass filter for the GSM1800 cellular radio was designed and fabricated. The size of the filter was 4.5mm×3.2mm×2.0mm. The properties of the fabricated filter are $f_0 = 1873$ MHz, bandwidth ~200MHz, insertion loss=0.52 dB, ripple < 0.5dB, attenuation > 35dB at $f_0 - 470$MHz. SEM and EDX were used to verify a limited diffusion of inner silver electrode during the sintering process. This LTCC material system is suitable for high-density multilayer interconnect for wireless telecommunication as well as other applications.

Key words:

LTCC, Multilayer, Bandpass Filter, and High Density Interconnect.

1. Introduction

Wireless telecommunication is one of the fastest growing electronic industries in recent years. More than two hundreds and eighty millions handsets were sold worldwide in 1999 alone. The annual growth rate of the handset is more than 50% in the last several years. Nokia predicts 1 billion population with cellular usage will be reached in year 2002.

Inside cellular phones, the components and modules in the RF (radio frequency, 300 MHz ~ 3 GHz) front end are one of the most important circuits to these wireless communication systems. The bandpass filter, which rejects unnecessary signals, is an important component in the RF circuits. The filters and other RF components and modules require high quality factor property. Hence, dielectric ceramic is one of the best materials for this application. Dielectric resonator (DR) type filters have long been used for this application. However, in order to meet the demand of small, light weighed, and more functional handsets cellular phone, the components for this application are required to follow the trend toward miniaturization, high reliability, and low cost. Thus, multilayer chip bandpass filters were introduced. The multilayer chip type filters are relatively smaller, as compared to DR filters, and more cost-effective compared to SAW (Surface Acoustic Wave) filters.

H. Manadai, K. Kobayashi, and J. Sasaki introduced the BaO-SrO-SiO$_2$-ZrO$_2$ ceramic system, which was cofired with copper (Cu) at 1000°C for the fabrication of the multilayer chip LC filters. Another low temperature cofired ceramic (LTCC) system with various dielectric constants was selected to fabricate the multilayer chip type filters, which used silver as the internal conductor. The material was required to be sintered at 900°C or less due to the melting point of silver (961°C). Several research efforts also demonstrated using low temperature cofired ceramics to fab-
ricate T/R (transmission/receiving) switch modules, receiver modules, and Bluetooth RF modules, which successfully integrated matching circuits, filters, balun, and some other passive components. Currently, several LTCC material systems are commercially available but these materials are relatively expensive.

This work was aimed to develop a new low temperature cofired ceramic system, which included dielectrics and various conductor metals, for the application of RF components, modules, and high density interconnects at relatively low cost. Some patterns, such as, microstrip lines and resonators were designed and fabricated to characterize the high frequency properties of the material. Based on such experience and database, the multilayer chip bandpass filters for the receiving end of GSM1800 cellular radio were designed, simulated, and fabricated. The filters were measured and also discussed in this work. The microstructure of interface between the dielectrics and the metal conductors was characterized.

2. Experimental Work

A standard ceramic powder processing technique was used to prepare the low temperature sintered dielectric ceramic powders. The powders contained dielectric ceramic fillers and flux. The material was sintered at 860°C in order to be cofired with silver (Ag) conductor at a relatively short period, such as, 20 minutes, to minimize the Ag diffusion in the LTCC materials during the sintering process. The high frequency properties of this dielectric material were measured using the T-resonator test pattern.

Figure 1 shows the flow chart of the fabrication process for the test patterns and multilayer chip filters. The ceramic slurry, which composed of the aforementioned ceramic powders, dispersant, organic binder, plasticizer, solvent, and required additives, was prepared. The slurry was cast by tape casting machines (AEM Model 2140) to fabricate the ceramic green sheets. Silver powders and several inorganic additives were mixed with an organic vehicle, which was composed with dispersant, binder and solvent, to prepare the cofired silver conductor paste. It is important to have the conductor paste match the shrinkage with the aforementioned ceramic green sheets during the sintering process. The designed conductor patterns of either the test patterns or the multilayer filters were then screen printed on the top of the green sheets before being stacked and laminated in sequential order. The test patterns were designed to measure the properties of the developed LTCC material at the high frequency range. The design and simulation of the filters were performed using several kinds of computer software.

The laminated green sheet was then separated in the designed size by a high precision cutter (Pacific Trinetics Corp., Model CS-SAC). The de-binder and sintering processes of the separated green chips were carried out in a batch-type furnace. The ramping process for binder burnout is relatively slow as compared to the material sintering profile. The test pattern specimens and filters were sintered at 860°C for 20 minutes.

The sintered specimens were characterized. The density, composed crystalline phases, CTE, three-point bending strength, dielectric constant, and dielectric loss of the LTCC were measured. A vector network analyzer (HP 8753D) was used to measure the test pattern as well as the frequency response of the multilayer chip bandpass filters. A test kit with TRL (Thru-Reflect-Line) calibration set was designed for this measurement. Figure 1 shows the flow chart of the fabrication process for the multilayer chip filters from ceramic powder preparation to the component measurement.

3. Test Pattern and Filter Design
Since the wavelength of signals at the radio frequency range is comparable to the size of components, the conventional “lump” elements and circuits theory is not capable to describe the signal wave propagation. Instead, the “distributed” circuitry theory adopted in the radio and microwave frequency range \(^{11,12}\) is used. In the distributed circuits, the lump elements, such as, resistors, capacitors, inductors, and even the LC resonators, are replaced with various types of transmission lines. Hence, the task of filter design and simulation should combine the filter synthesizing and electromagnetic simulation.

The T-type resonators, as shown in Figures 2(a), (b), and line resonator (c) were used as the test pattern for measuring the property of the LTCC dielectric and the metallization conductor at the high frequency range. The line width is a function of the thickness of the substrate. There are several types of filters using the transmission line theory, such as, coupled bandpass filters, hairpin filters, combine filters, and other types\(^{11}\). The designed multilayer filter had 3-D circuit structure with the size of 4.5×3.2×2.0 mm\(^3\). In order to achieve the design and simulation for the multilayer chip filters, a filter synthesizing software as well as the 2.5-D or 3-D electromagnetic simulation software were used in this work.

4. Results and Discussion

4.1. Properties of Low Temperature Cofired Ceramic Material

The density of the LTCC material under test after being sintered at 860°C for 20 minutes is 3.5 g/cc. The average coefficient of thermal expansion of the ceramic is 4.5 ppm/°C from room temperature to 300°C, measured by a thermal mechanical analyzer (TMA, Perking Elmer, Model 7 Series). The bending strength of the sintered LTCC rods was measured by a three-point bending approach. The average bending strength of the LTCC material was 1998 kg/cm\(^2\). The temperature coefficient of capacitor (TCC) of the material is 8.5 ppm/°C from –40° C to 85°C. Since the temperature coefficient of resonant frequency (\(\tau_f\)) of the material was described as \(\tau_f = -1/2 \ \text{TCC} - \ \text{CTE}\). The \(\tau_f\) was calculated to be equal to -8.7 ppm/°C.

The dielectric constant and quality factor of the LTCC were measured at 1 MHz as well as at 2~3 GHz. The T-resonator test pattern, as shown in Figure 2, was used to measure the material properties at radio frequency. The thickness of the LTCC substrate was about 0.5mm with T-type silver pattern and silver ground plane printed on the top and bottom of the substrate, respectively. The printed substrate was then cofired at 860°C. It is important to have the sintering shrinkage and the thermal expansion of the LTCC material match with that of the silver conductor paste. Hence, the test pattern substrate would not be cambered after the cofiring process. Generally, the camber occurred due to the uneven shrinkage of LTCC and silver conductor paste. Figure 3 shows the frequency response of the T-resonator on the LTCC substrate. The resonant frequency of the T-resonator is at 2.1GHz. From this frequency response, the dielectric constant and the quality factor of the LTCC material were calculated. The dielectric constant of the LTCC was about 7.75 ~ 7.9 at 1 MHz and 2.1 GHz. The quality factor of the material was 1100 at 1MHz, and dropped to about 500 at 2.1GHz. The properties of the LTCC material are listed in Table 1.

![Figure 2. Schematic structure for (a) Short T-resonator, (b) Long T-resonator, and (c) Line resonator.](image)

![Figure 3. Frequency response (S21) of T-type resonator of the LTCC test pattern.](image)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dielectric Constant, K</td>
<td>7.8</td>
</tr>
<tr>
<td>Q (@ 1MHz)</td>
<td>1100</td>
</tr>
<tr>
<td>Q (@ 2.1GHz)</td>
<td>500</td>
</tr>
<tr>
<td>(\tau_f) (ppm/°C)</td>
<td>-8.7</td>
</tr>
<tr>
<td>Thermal Expansion Coeff. (ppm/°C)</td>
<td>4.5</td>
</tr>
<tr>
<td>Bending Strength (kg /cm(^2))</td>
<td>1998</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>3.5</td>
</tr>
<tr>
<td>Sintering Temperature (°C)</td>
<td>860</td>
</tr>
<tr>
<td>Sintering Time (minutes)</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1. Properties of the low temperature cofired dielectric material.
4.2. Properties of Cofired Silver Conductor Metallization

The quality factor of the test pattern or filters ($Q_{\text{total}}$) is related to the dielectric quality factor ($Q_d$) and the quality factor of metal ($Q_m$). The relation can be described in the following equation,

$$\frac{1}{Q_{\text{total}}} = \frac{1}{Q_d} + \frac{1}{Q_m}$$

Hence, the $Q_{\text{total}}$ is controlled by the smaller value of $Q_d$ and $Q_m$. It is substantial to understand the characteristics and the properties of metal conductors on the ceramic substrates. Since the melting point of silver is 961°C, the sintering temperature of pure silver conductor is far below that of LTCC material. Some inorganic additives were added to the silver conductor paste to detain its sintering process to higher temperatures and also varied its sintered shrinkage in order to match with LTCC green sheet. However, the inorganic additives (non-conductive material) degraded the conductivity of the silver metallization. Table 2 illustrates the unloaded quality factor of T-type resonators and line resonator for three conductor pastes on alumina substrates. It would be easy to compare the conductivity of the silver conductor paste. The silver conductor paste (MRL 1022) developed in this work exhibited the highest quality factor and thus the highest conductivity compared to the other two commercially available conductor pastes. Moreover, the MRL 1022 paste is perfectly matched with the sintered shrinkage of the LTCC green sheet under investigation.

Table 2. Quality factor of T-type and the line-type resonator using three conductor pastes on alumina substrates.

<table>
<thead>
<tr>
<th>Metal Paste</th>
<th>Du Pont</th>
<th>Ferro</th>
<th>MRL1022</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q (Short T Resonator)</td>
<td>@2.56 GHz</td>
<td>@2.55 GHz</td>
<td>@2.54 GHz</td>
</tr>
<tr>
<td>Q (Long T Resonator)</td>
<td>@1.64 GHz</td>
<td>@1.64 GHz</td>
<td>@1.66 GHz</td>
</tr>
<tr>
<td>Q (Line Resonator)</td>
<td>@2.03 GHz</td>
<td>@2.03 GHz</td>
<td>@2.04 GHz</td>
</tr>
</tbody>
</table>

4.3. Properties of the Multilayer Chip Bandpass Filters

The targeted filters was designed for the receiving end of DCS1800 cellular phones with its central frequency ($f_0$) = 1842.5MHz. The size of the filter is about 4.5 mm×3.2 mm×2.0 mm. Six layers of conductor patterns were designed and connected by its side electrodes. The ceramic green sheets were printed with designed conductor patterns and then aligned, stacked, and laminated by an isotropic press using hot water bath. The thickness of each layer of the green sheets is required to meet the designed configuration. A high precision cutter separated the green chips of the filters from the laminated green sheets. The chips were maintained at 500°C for binder burnout and then sintered at 860°C for 20 minutes. The measured frequency response of the filters is illustrated in Figure 4. The property of the fabricated multilayer chip bandpass filter is listed in Table 3.

Table 3. Properties of multilayer chip bandpass filters.

<table>
<thead>
<tr>
<th>Property</th>
<th>Designed Value</th>
<th>Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Size (mm)</td>
<td>4.5×3.2×2.0</td>
<td>4.5×3.2×2.0</td>
</tr>
<tr>
<td>Central Frequency (MHz)</td>
<td>1842.5</td>
<td>1873</td>
</tr>
<tr>
<td>Insertion Loss (dB)</td>
<td>2.0</td>
<td>0.52</td>
</tr>
<tr>
<td>Ripple in pass band (dB)</td>
<td>&lt;0.5</td>
<td>&lt;0.5</td>
</tr>
<tr>
<td>Band Width (MHz)</td>
<td>&gt;75</td>
<td>200</td>
</tr>
<tr>
<td>Attenuation (dB, @ fo – 470 MHz)</td>
<td>&gt;25</td>
<td>&gt;25</td>
</tr>
</tbody>
</table>

The central frequency of the fabricated filters shifts from the designed value about 30 MHz higher. Since the bandwidth is relatively larger than the required pass band (75MHz), the shift of central frequency is acceptable to the application. The property of the fabricated multilayer chip bandpass filter was similar to that of the designed filter except the central frequency. The insertion loss is relatively small (0.52 dB) due to its wide bandwidth. The measured results verified the properties of the developed LTCC material system, which is capable to be used to fabricate RF components and modules.

Figure 5 indicates the result of microstructure and EDS (Energy Dispersive Spectrometry) analysis of the interface between the LTCC dielectric and the silver conductor of the aforementioned bandpass filter. No Ag diffusion after sintering process was observed by the microstructure observation and EDS analysis. It may be attributed to the sintering process at a relatively low temperature (860°C) and a short soaking time (20 minutes).
5. Conclusion

A low temperature sintered ceramic was developed with a cofired Ag internal conductor paste. The dielectric constant is 7.8 and the quality factor is larger than 500 at 2.1GHz. The material was sintered at 860°C for about 20 minutes. A multilayer bandpass filter was designed and simulated with $f_0 = 1842.5$MHz. The multilayer ceramic processing was used to fabricate this filter. The size of the filter is 4.5 mm×3.2 mm×2.0 mm. The properties of this fabricated filter is $f_0 = 1873$ MHz, bandwidth = 200MHz, insertion loss = 0.52 dB, ripple <0.5dB, and attenuation >25dB at $f_o$, 470MHz. The variation of the central frequency is shifted 30 MHz higher form the designed value. It can be turned to its correct frequency by the capacitance adjustment of the filters. Through the verification of the fabricated bandpass filter, the LTCC material system is capable to be used to fabricate the high density interconnect for the radio frequency application.

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Reference

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