# Achieving Ceramic-like RF Capacitor Requirements with Organic-based Materials

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## Abstract

*New and novel organic-based composite materials for the use of embedded RF capacitors have been developed to address the important material issues by means of functional filler and resin chemistry. Combining different fillers with appropriate chemistries, the net composite can be made thermally stable while retaining the high dielectric constant and low loss. These composites attained dielectric constant of above 7 without compromising the quality factor in GHz frequency range. In addition, measurement of capacitance variation as a function of temperature (TCC) showed flatter TCC profile, resulting in TCC of ±30 ppm/℃ over the temperature range -55 ℃ to 125 ℃. It can be incorporated into organic chip package and, unlike ceramic-based LTCC they can utilize large area processing that is typical, and available in high volume manufacturing. This material is formulated for RF module designers to successfully implement embedded RF capacitors into their organic chip package designs and thus improve form factor, electrical performance and possibly reduce overall costs.*

Key words: embedded capacitor, RF, dielectric constant, composite, TCC

## Introduction

Embedded capacitors for printed circuit board (PCB) have been extensively explored, especially for digital functions such as decoupling in the high-end computing industry, mostly for telecom and networking applications [1]. For these types of applications, the inductance of the power distribution network (PDN) is the prevailing factor and embedded capacitor technology has been utilized to improve signal integrity, reduce impedance and dampen noise. To date, however, it has been more difficult to use embedded capacitors as part of RF circuits such as filters. There are several reasons, besides the circuit design issue, which cause this and they are primarily due to the fact that most materials used for forming embedded discrete capacitors have relatively high loss and low dielectric constant (at GHz frequencies). Also, the capacitance can easily change as a function of temperature, influencing the total system performance.

Most RF communication and mixed signal systems need capacitors with very high tolerance and stable properties with temperature and humidity for efficient design [2]. Currently there is no solution for low cost embedded RF capacitor technology. Most RF/Microwave modules are manufactured using LTCC (Low Temperature Co-fired Ceramics), the base inorganic material being very stable both thermally and electrically. However, LTCC technology needs an expensive sequential multilayer fabrication process and has low component density integration capability. It is also limited by its incompatibility with large-area processing. The result is that designers are seeking alternatives to LTCC and organic packages are the leading choice [3].

Emerging applications with embedded RF capacitors require the development of organic compatible dielectric materials with thermally stable high dielectric constant (D*k*), low dielectric loss (DF) and improved electrical performance at GHz frequency range. RF capacitors are needed for filtering (<10pF) and capacitive coupling (<500pF) and require a Q of >200 to meet the performance requirements. In addition, for many applications, the capacitance value has to be stable, preferably within 0.3 percent over a wide range of temperature which means TCC (Temperature Coefficient of Capacitance) of within ±30ppm/℃. In the present study, new and novel high D*k* compositions to achieve high Q (low loss) and flatter TCC have been engineered using the composite approach with ceramic fillers and polymers to replace LTCC components such as capacitors.

## Functional filler/resin chemistry and TCC

Fig. 1 shows the relation between TCC and D*k* of various composites investigated. TCC is very important parameter for RF capacitors and is becoming critical for various RF applications because of the tighter design tolerances. The TCC values can be calculated from the measured capacitance data with temperature using the following equation: TCC = $(C_{85℃}-C_{25℃})/(60\times C_{25℃})$, where TCC: temperature coefficient of capacitance (/℃), $C_{85℃}$: capacitance at 85℃, $C_{25℃}$: capacitance at 25℃. This definition is used in discrete capacitors (NPO type: ±30ppm/℃, -55℃ to 125℃) and would also be applicable for embedded RF capacitors. Any deviation in component specifications with temperature can adversely affect the frequency selection characteristics of the filter or resonator circuits in RF modules. TCC can be either positive or negative for both polymers and ceramic functional fillers. As seen in Fig. 1, the (-) TCC region and (+) TCC region are separated by the selection of materials. Since a high dielectric constant invariably comes with either a negative or positive TCC, the ceramic functional fillers should be carefully selected to compensate for each other or compensate with the polymer TCC, leading to a lower, flatter TCC.

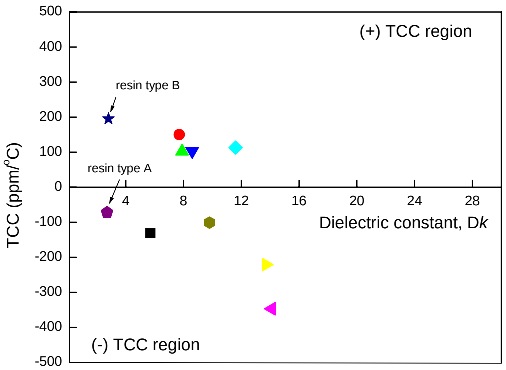

Fig. 1. TCC *vs.* dielectric constant of various composites developed based on two different resins.

The typical TCC profile of the selected composition is shown in Fig. 2, and TCC rotates counterclockwise as a function of compositional change. Remarkably, one of the compositions has TCC of ±30ppm/℃ all over the temp measured. It was determined that these materials were optimized with regard to special temperature characteristics.

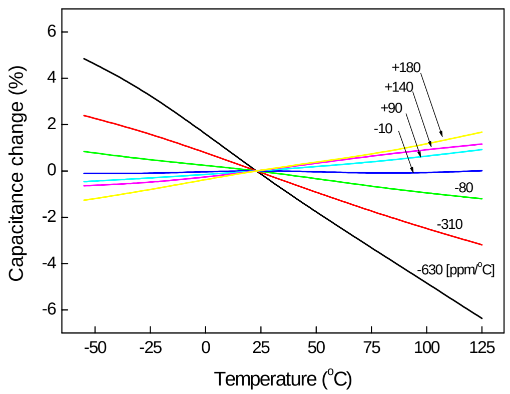

Fig. 2. Typical TCC of the composite as a function of compositional change

## Material Characteristics and Performance

Fig. 3(a) shows D*k* and DF of composites having different filler/resin chemistry at 10GHz and Fig. 3(b) represents the TCC of the composites. The basic polymer (composite A) typically has D*k* between 2 to 3, DF 0.002 and TCC of -72ppm/℃. This low D*k* does not provide enough capacitance density to replace the pF size capacitors we are interested in within the allowable device area. In order to push up the capacitor density, typical ceramic particles were added to the polymers. Note that D*k* moves up to ~18 while keeping DF stable to 0.002 at 10GHz in composition (C). However, in this case, it has a negative TCC behavior over the temperature range, showing its value of about -412ppm/℃. Existing data indicates that they still have high thermal instabilities exceeding -400ppm/℃ and it is not possible to meet the tightest requirements of discrete capacitors for RF components. To improve TCC variation, different fillers were evaluated, but to flatten the response we had to sacrifice the D*k* in composition (B).

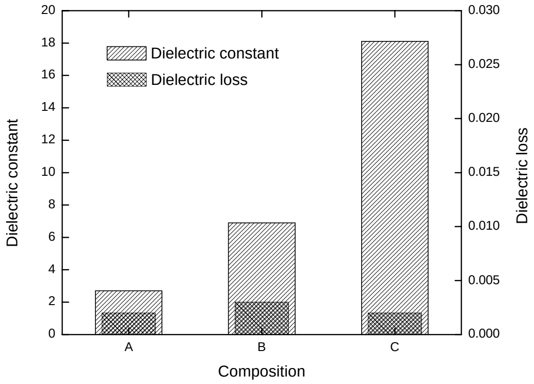

Fig. 3(a) Dielectric constant, D*k* and DF of composites with different filler chemistry.

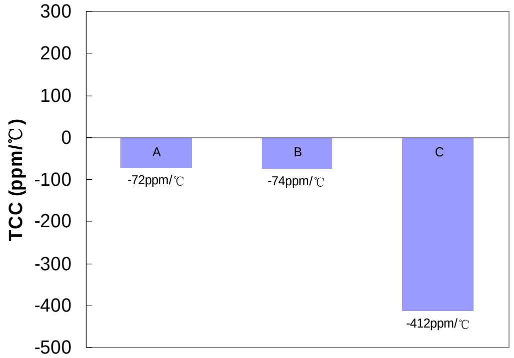

Fig. 3(b) TCC of composites

We investigated the stability of the composite (composition B in Fig. 3) with frequency and it shows useful trends such as paraelectric-like frequency stable properties with low loss. The material having D*k* of about 7 exhibited low DF (0.002), which was almost independent of the frequency to 10GHz. The measurement technique at ㎓ frequency range was described elsewhere [4].

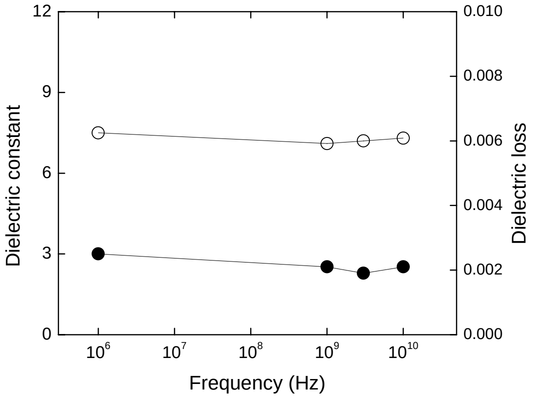

Fig. 4. Frequency stability of D*k* and DF of comp B

It is well known that most polymers are moisture sensitive. Although the embedded capacitors will be inside the module, they still can be subject to moisture that may penetrate the surrounding material, which could affect the electrical and mechanical properties. In order to test the susceptibility of the composite, capacitors were formed on a laminate and it was exposed to 85% RH at 85℃ for 1000hrs. The materials were pulled periodically during this test and D*k* was measured at 1MHz. As shown in Fig. 5, no significant change in D*k* was observed and thus this exposure did not affect the capacitance of the material.

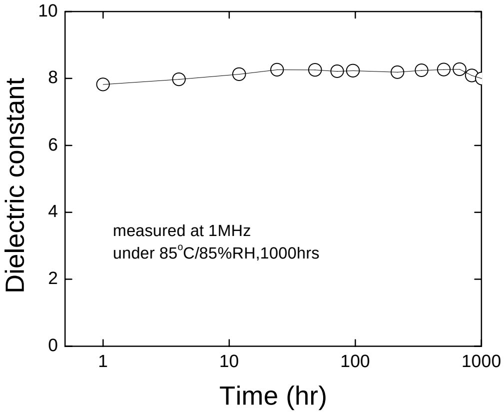

Fig. 5. Moisture affect on capacitor material

Most capacitors suffer a degradation of leakage current when subjected to sufficient voltage-temperature stress, and embedded RF capacitors are no exception. In addition to make sure that the material will pass the standard reliability tests, THB (Temperature, Humidity, and Bias) test were performed using discrete capacitors as we did for the moisture test previously described. Electrodes were soldered to the top and bottom electrodes and a 20 volt bias was applied to the capacitors. The laminate was placed in the temperature and humidity controlled oven and run until a 10% change in resistance occurred or 1000 hours (whichever came first). It turned out that the material held steady for the 1000 hours. (Fig. 6) Thus the material should be acceptable for an extended period of time for applications under 20 volts. In addition to the above performance factors, all the standard tests including, solder shock, solder float, Time to Delamination (at both 260℃ and 288℃) and high potential testing were performed and all these tests passed.

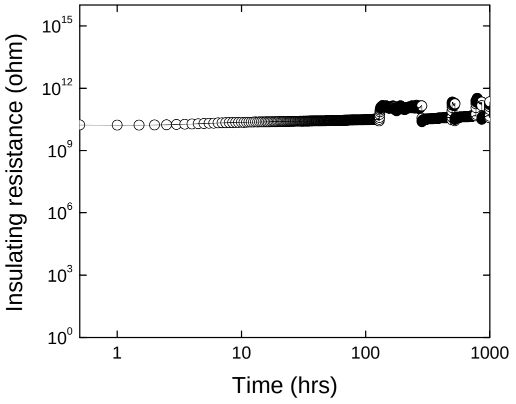

Fig. 6. Temperature, humidity and bias test at 20V

The typical property of this material is summarized in Table. 1. The data is based on a dielectric thickness of 25㎛.

Table. Typical properties of FaradFlex, MC25LD.

| Properties | unit | MC25LD |
|---|---|---|
| Material System | type | resin/ceramic filler |
| D*k* (1㎒/1㎓) | | 7.5/7.1 |
| DF(1㎒/1㎓) | | 0.0025/0.0025 |
| Capacitance density @1㎒ | nF/㎠ | 0.26 |
| TCC | ppm/℃ | -60 |
| Peel Strength | kN/m | 0.90 |
| Thermal Stress, 20s@288℃ | 10x | PASS |
| Tg (DMA, Tan d) | ℃ | 215 |
| CTE (TMA, α1/α2) | ppm/oC | 55(α1) |
| Thermal Conductivity | W/mK | - |
| Reflow Test, 20s@260℃ | | PASS |
| THB, 85℃/85%RH/dc bias | >1000hr | PASS |
| PCB process | | Sequential |

## Formation of Embedded Capacitors

One of important strategic parameters for RF capacitors is the tolerance and it depends on PCB process variation as well as the material. Fig. 7 shows the relative idea, the approximate area needed to make various size pF capacitors. Discrete surface mount capacitors can be purchased with fairly tight tolerance. plus or minus 1% of nominal value is readily available and usually not at a big price premium over lower tolerance capacitors. Because of this, designers usually specify the tighter tolerances whether or not the circuits require them. However, when forming discrete capacitors inside the module, the materials and processes don't currently allow for these types of tolerances. With proper process optimization and control, we can still achieve values that will result in highly functional circuits. The use of proper dispersion techniques for the ceramic filler in the polymer and the right coating method for putting the polymer on the copper can result in fairly tight material tolerances. Our internal testing of laminates indicates that it is possible to hold better than +/- 5% with +/- 3% being achievable. In addition to the material variation, the formation of the electrodes by the etching process will also add to the tolerance. We may have this expected tolerance when assuming ±10㎛ etching tolerance at a board shop as a process variation. For larger capacitors (<100 pF) an additional +/- 1% can be expected and for the smallest (<5 pF) there can be additional +/- 5 to 10% to the tolerance. Use of thinner copper foils and laser direct imaging can help minimize the variation.

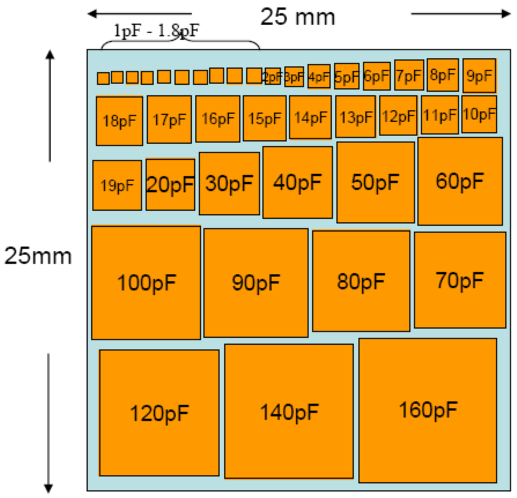

Fig. 7. Area required for embedded capacitors

## Conclusions

Applications with embedded RF capacitors require organic compatible dielectric materials with thermally stable high dielectric constant, low loss and improved electrical performance at GHz frequency range. It has been demonstrated that by carefully selecting the right polymers and fillers, materials can be provided which maintain capacitance values to within 0.3 percent over a wide range of temperatures and be stable with respect to moisture and frequency. Capacitor tolerances of +/- 10% or better can be achieved based on material and process tolerances, as well as the capacitor value.

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