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Miniature Low-Pass Filters in Low-Loss 9k7 LTCC

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Abstract

DuPont 9k7 low-temperature cofired ceramic (LTCC) is a low-loss, or high-quality-factor Q, tape system targeting at radio frequency (RF) applications. This paper reports on the effect of a critical process parameter, the heating rate, on the densification and dielectric properties of the 9k7 LTCC. The role of competing densification and crystallization during the sintering of 9k7 is discussed. The high Q of DuPont 9K7 can be used to improve RF system performance, for example a better receiver noise figure, by designing embedded passive RF components such as inductors, capacitors and filters. Miniaturized multilayer low-pass filters (LPF) with a wide stopband were fabricated to showcase the technology.

Keywords: Low-temperature cofired ceramics (LTCC), multilayer, miniature low-pass filter.

I. Introduction

LTCC is a microelectronics multilayer 3D packaging, interconnection, and integration technology. An LTCC system refers to a base tape dielectric, typically a crystallizable glass or a glass and ceramic composite, along with low-temperature-sintering metal conductors (Au, Ag, Pt, etc.) that are cofired at 850 ~ 900 °C. In the last two decades, the application of LTCC technology has grown the most in wireless communications ranging from radio (RF) to microwave (MW) frequencies. The three dielectric material parameters most important to this application space include the dielectric constant, ε, the quality factor, Q (i.e. where Q = 1/dielectric loss), and the temperature coefficient of resonant frequency, τ_f.

It is widely recognized that the residual glass in a sintered LTCC dielectric is the main contributor to overall dielectric loss [1]. To minimize dielectric loss in a LTCC dielectric, a common practice is to limit the amount of residual glass in the sintered dielectric. This is achieved by designing the glass composition and the sintering profile to induce devitrification to maximize the amount of crystalline material in the sintered LTCC.

The DuPont™ GreenTape™ 9k7 LTCC system [2] is a low-loss tape system designed for high-frequency applications. Unfired 9k7 tape consists of a crystallizable glass and alumina filler, along with organic vehicles. During sintering, the glass both partially crystallizes to form self-derived crystalline phases, and reacts with alumina to form reaction-derived crystalline phases. A low dielectric loss is achieved by minimizing the amount of residual glass via multiple crystallizations. In addition, the self-limiting depletion of the "network"-modifying ions in the glass adds to the re-firing stability.

The glass in 9k7 LTCC has multiple roles, including enabling densification, devitrifying, and reacting with filler material to form multiple low-loss crystalline phases. The paper addresses both densification and crystallization during 9k7 sintering, including optimizing the firing schedule to reach the highest density with the maximum level of crystallization.

LTCC is one of the technologies that are capable of component integration. LTCC offers layout flexibility and three-dimensional integration capability to produce embedded passive components, for example, inductors, capacitors, filters, and antennas [3–6]. The low-pass filter (LPF) is a key passive component that is widely used in wireless systems to filter out unwanted signals. Many compact and high-performance LPFs using different fabrication technologies can be found in references [7–9]. This paper demonstrates a new miniaturized LPF with a wide stopband bandwidth fabricated in 9k7 LTCC. The new filter is verified by electromagnetic simulation and S-parameter measurement.

II. 9k7 LTCC Dielectric

Details of structure characterization of 9k7 LTCC dielectric, including crystallization and phase identification, can be found in a previous publication [10]. Fabrication of dielectric test coupons and measurement of RF properties were also presented in the same reference. The following sections highlight critical material properties of 9k7 LTCC for the design of RF components.

(1) *Densification of 9k7 LTCC*

Fig. 1 shows the Z (thickness) shrinkage from the dilatometer measurement of 20-layer laminated 10-mil-thick 9k7 tapes at heating rates 1, 2, 3, 4, 5, 6, and 8 K/min to 800 °C. It is clear that, at all heating rates, shrinkage is complete well below 800 °C. However, the net Z shrink-

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age and densification, measured between the onset and the end of a shrinkage curve, increase with heating rate.

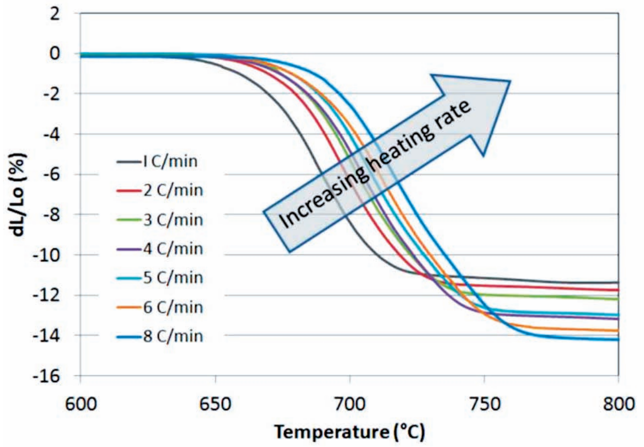

Fig. 1 : Z shrinkage of 9k7 at different heating rates.

The effect of the heating rate on 9k7 shrinkage can be attributed to the inhibition of densification by crystallization. At low heating rates, the crystallization has sufficient time to occur prior to densification. The depletion of "network-forming" ions in 9k7 glass increases the viscosity of the glass, which consequently inhibits densification, and results in less shrinkage and a lower density. At very high heating rates, the densification occurs before the onset of crystallization, allowing the glass-ceramic to reach full density followed by crystallization. At heating rates between the two extremes the densification and crystallization might occur simultaneously, though the competing processes depend strongly on the glass chemistry and the actual heating rate.

(2) 9k7 Shrinkage and dielectric properties

Fig. 2 shows the XY&Z shrinkage and sintered density as a function of the heating rate. Consistent with the dilatometry measurement, relatively low shrinkage and sintered density are seen at 1 K/min. As the heating rate increases, both shrinkage and density continue to increase. However, the rate of change decreases as the heating rate increases. Beyond 5 K/min, the Z shrinkage reaches a plateau, while the XY shrinkage and sintered density still show a nominal increase. Again, the change in densification behavior, especially the relatively large changes in shrinkage and sintered density at low heating rates, might be attributed to crystallizations of 9k7 during sintering.

Fig. 3 presents corresponding dielectric constant and quality factor Q measured at approximately 9.5 GHz. With increasing heating rate the dielectric constant follows a same trend as the shrinkage as well as density curves, increasing from 6.58 at 1 K/min to 7.32 at 5 K/min, and eventually approaching a plateau of 7.53 at heating rates 6 K/min to 8 K/min. The data strongly suggest that at a slow ramp rate the 9k7 dielectric does not reach full density, resulting in a relatively porous structure, and thus, a lower dielectric constant. It should be noted that the heating rate in the manufacturer's recommended cofiring profile is approximately 2.5 K/min [see DuPont 9k7 datasheet]. The nominal dielectric constant of 7.1 obtained using this sintering profile falls right in between the dielectric constants of 6.98 at 2 K/min and 7.14 at 3 K/min from current study.

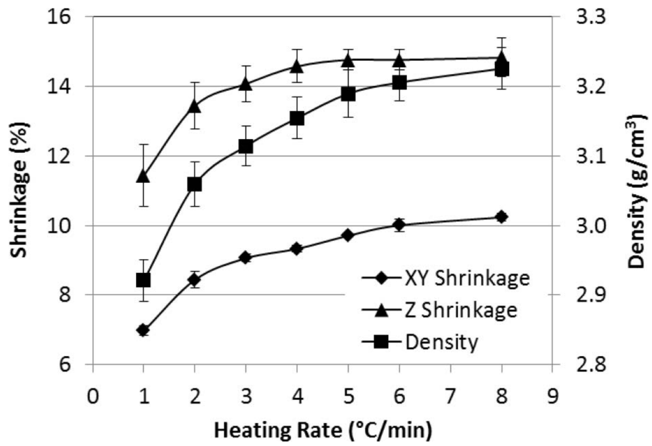

Fig. 2 : XY and Z shrinkage and bulk density versus heating rate.

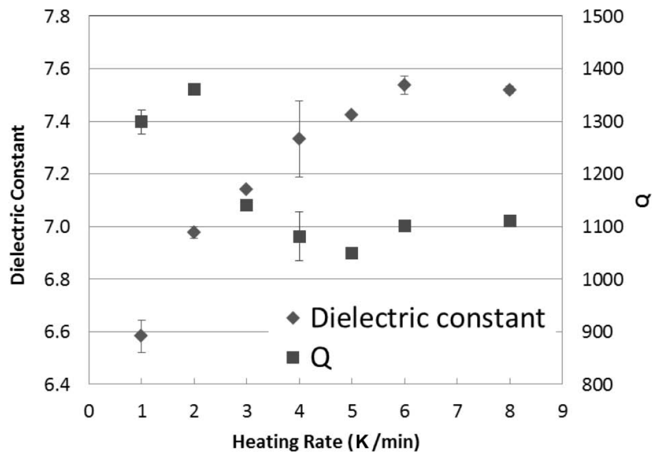

Fig. 3 : Dielectric constant and Q. measured at 9.5 GHz, as a function of heating rate.

Reproducibly achieving a high density is essential for consistent dielectric constant, since the porosity in a lower relative density LTCC dielectric generally reduces the dielectric constant of the substrate. Ideally a high heating rate that drives full densification, followed by the desired crystallization, is preferred. For 9k7 LTCC dielectric a heating rate ≥ 5 K/min appears to be necessary to achieve the objectives. A dielectric constant equal to 7.4, achieved with a heating rate of 5 K/min, for the 9k7 LTCC is used for RF design and simulation in this study.

III. LPF in Multilayer 9k7 LTCC

(1) Filter design

A simplified basic structure of the LTCC-fabricated LPF is shown in Fig. 4. Different from the two-dimensional LPF in [7], the new miniaturized LPF is achieved by folding its capacitive and inductive-meander strips in z dimension to create a more compact size in x-y dimensions. The top and bottom ground planes are not shown.

Figs. 5(a) to 5(f) show the individual conductor layer and via connection of the LPF. A total of eight layers 9k7 tapes were used for filter fabrication. The metals 1 and 5 are used to increase the gap capacitance. Metals 2 and 4 are the folded capacitors. The vias connecting the two capacitive strips were designed to suppress the second harmonic of the filter to obtain a wide stopband. The top conductor pattern with I/O pads is shown in Fig. 5(f). The solid ground plane at the bottom of the filter matches the foot print of the top conductor pattern. The size of fired LPF is 5.3 x 3.9 x 1.72 mm.

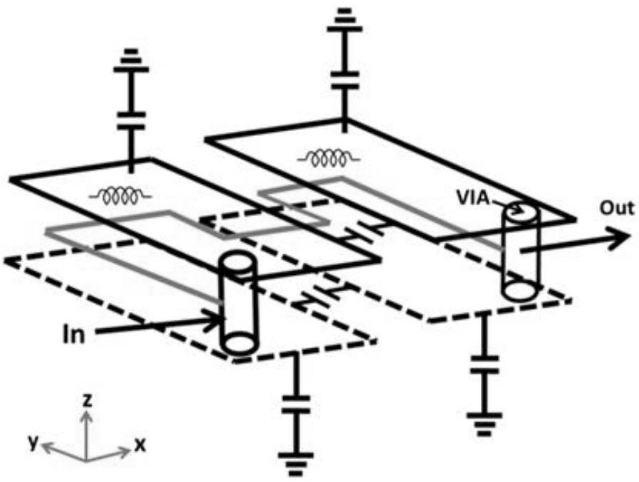

Fig. 4 : Simplified three-dimensional LPF structure.

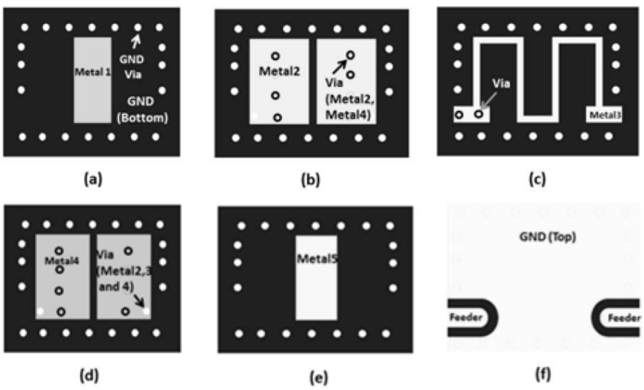

Fig. 5 : Metal layers of the filter. (a) metal 1 at layer 8 with solid ground plane at the other side (bottom), (b) metal 2 at layer 7, (c) metal 3 at layer 5, (d) metal 4 at 3, (e) metal 5 at layer 2 and (f) top conductor pattern at layer 1.

(2) Filter fabrication

9k7 LTCC tapes at the thickness 254 μm unfired, and approximately 222 μm fired, were used for filter fabrication. Gold-based pastes were used as the conductors, include DuPont TC501 Au for via fill and screen-printed TC502 Au for internal signal lines as well as internal/external ground planes. All panels were laminated using a standard process that included 20.7 MPa isostatic pressing at 70 °C for 10 minutes. The laminated LTCC panels were sintered at 850 °C for 30 min in air on Al_2O_3 setters. The sintered LTCC panels were diced to singulate individual LPFs.

(3) Simulated and measured results

The S parameters of LPFs were measured over 0 to 7.5 GHz at room temperature. The filter has a 3-dB passband from DC to 1.5 GHz. The insertion loss is less than 0.37 dB from DC to 1.28 GHz. The return loss is better than 13 dB from DC to 1.3 GHz. The stopband rejection is greater than 22 dB from 2.3 GHz to 7.5 GHz.

The S parameters of the LPF were simulated using a Keysight ADS electromagnetic simulator. Fig. 6 compares simulated and measured results. Excellent agreement between the simulation and measurement was achieved for the S11 parameters. The variations between measurement and simulation on S21 were attributed to the manufacturing tolerances in the fabricated strip circuits.

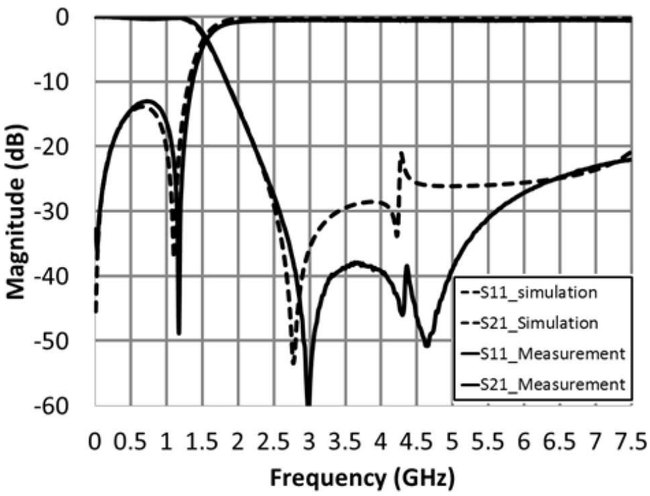

Fig. 6 : Simulated and measured filter S parameters.

IV. Conclusions

The effect of the heating rate on the shrinkage, density, and dielectric properties of 9k7 LTCC has been studied. The results clearly demonstrate that crystallization affects the densification behavior and properties of the 9k7 LTCC. At low heating rates, crystallization appears to inhibit the densification of the 9k7. To achieve process stability and consistent dielectric properties, a heating rate that initially allows full densification followed by crystallizations is necessary.

A compact elliptic-function LPF with high selectivity and a wide stopband was designed and fabricated using 9k7 LTCC. The size of the miniaturized filter is 5.3 x 3.9 x 1.72 mm. The filter has a 3-dB passband from DC to 1.5 GHz and better than 22 dB stopband rejection from 2.3 GHz to 7.5 GHz. The measured filter parameters agreed well with results from the electromagnetic simulation.

Acknowledgements

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