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Measurements of loss tangent and relative permittivity of LTCC ceramics at varying temperatures and frequencies

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Abstract

Precise knowledge of microwave properties of LTCC materials is crucial for efficient design of microwave systems, especially for design of communication filters. In this paper relative permittivity ε_r and loss tangent tanδ of a variety of LTCC ceramics manufactured by Heraeus Circuit Materials Division are presented for frequencies of 3.3 and 5.5 GHz at room temperature and also for temperatures varying from −33 °C to 22 °C at a frequency of 3.3 GHz. The measurement system for microwave characterisation of LTCC materials was based on the split post dielectric resonator and the Transmission Mode Q-factor techniques with random uncertainty in ε_r and in tanδ better than 0.5 and 2.6% respectively.

Keywords: Dielectric properties; LTCC; Substrates; Measurement system

1. Introduction

The integration and miniaturization of passive circuits have lagged significantly in developments in electronic circuits containing active elements for several years. Low temperature co-fired ceramics (LTCC) allow three-dimensional circuits to be constructed within a ceramic block that enables 'burying' of passive elements: resistors; inductors and capacitors. The LTCC technology has provided a much needed advance in the miniaturisation of devices, however materials used in the past required firing temperatures that were too high to allow the use of highly conductive and low loss materials essential for superior performance. In addition, a serial processing was required in the circuit construction, resulting in long manufacturing times. Hence until recently LTCC materials found limited applications.

In the last few years the increase in the level of functions required of wireless communications has necessitated the use of higher frequency ranges. Also demands of consumers for faster, smaller, and cheaper communication devices have put pressure on the wireless communications market to integrate passive elements and resulted in significant advances in manufacturing and properties of 3D LTCC circuits.[1–4] All layers can be now processed in parallel, reducing the production cost and time.

Lower temperature firing of ceramic blocks allows utilization of highly conductive metals such as gold or silver and decrease of line-loss. As a result of this progress a very rapid growth of applications of Low temperature co-fired ceramics in wireless communications has been observed recently. This phenomenon is directly related to the ability of the LTCC technology for parallel processing, precisely defined parameters and stable performance over the lifetime, high performance conductors, three-dimensional microwave structures and very high density of interconnects.

Currently LTCC materials are manufactured by several companies and exhibit ε_r from 3.9 to 10 or more and loss tangent of below 0.005 at frequency of 5 GHz. As frequencies of wireless MMIC systems increase toward 40 GHz and above for many applications, device performance and circuit technology become increasingly critical. Hence decrease of losses of LTCC

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materials is particularly important for future progress in LTCC wireless applications. Accurate measurements of loss tangent and the real relative permittivity at microwave frequencies still represent a complex problem. In this paper we present precise measurements of LTCC materials from four differing manufacturing technologies using the split-post dielectric resonator technique and data processing by the Transmission Mode *Q*-Factor technique.

2. Low temperature co-fired ceramics tested

Four different LTCC materials were tested, three manufactured by Heraeus CMD[3,4] and one other material (CTX). The Heraeus materials were:

CT700, a long established general purpose, lead free LTCC material,
CT800, a modified version of CT700,
CT2000, a material developed for microwave use with a low loss and low temperature coefficient of frequency—T_f

Tested LTCC samples were 52 mm by 52 mm of thickness as listed in Table 1.

3. Split-post dielectric resonator, measurement system and computations procedures for characterisation of LTCC materials

Split-post dielectric resonators (SPDR) have been used for measurements of microwave properties of substrate materials for MMIC since 1981.[5–12] In this technique a tested substrate is placed between two low loss dielectric rods situated in a metallic enclosure, as shown in Fig. 1. Typically $TE_{01\delta}$ mode is used for microwave characterization of dielectric substrates since this mode is insensitive to the presence of air gaps perpendicular to *z*-axis of the resonator.

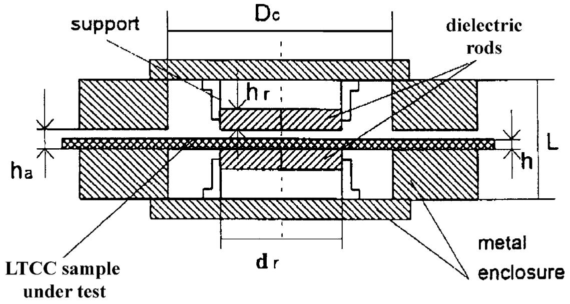

Fig. 1. Split-post dielectric resonator.

The real part of the samples' complex permittivity is computed from measured resonant frequencies of the resonator using the following equation[12]:

$$\varepsilon_r' = 1 + \frac{f_0 - f_s}{h f_0 K_\varepsilon\left(\varepsilon_r', h\right)} \tag{1}$$

where: h is the thickness of the sample under test, f_o is the resonant frequency of the empty SPDR, f_s is the resonant frequency of the resonator with the dielectric sample. K_ε is a function of ε_r' and h, and has been evaluated for a number of ε_r' and h using Rayleigh–Ritz technique. Iterative procedure is then used to evaluate subsequent values of K_ε and ε_r' from Eq. (1).

The loss tangent of the tested substrate is calculated from the measured unloaded Q_o-factors of the SPDR with and without the sample based on Eq. (2)

$$\tan\delta = \left(Q_0^{-1} - Q_{DR}^{-1} - Q_C^{-1}\right)/\rho_{es} \tag{2}$$

where p_{es} is electric energy filling factor of the sample, Q_{DR}^{-1} and Q_c^{-1} denote losses of the metallic and dielectric parts of the resonator respectively.

The numerical procedure of permittivity and loss tangent computations has been based on the rigorous electromagnetic modeling of the split-post resonant structure using the Rayleigh–Ritz technique. The procedure has been described in detail in[12] and it has been

Table 1
Measured dielectric properties and calculated measurement errors of LTCC samples at frequencies 3.3 and 5.5 GHz at room temperature

Sample	Thickness (mm)	Freq. (GHz)	ε_r	Tanδ	Random $\Delta_r\varepsilon_r$ in % for $\Delta h = 3$ μm	Random $\Delta_r\tan\delta$ in % for $\Delta_r Q_o = 1\%$	Absolute $\Delta_r\tan\delta$ in % for $\Delta_r Q_o = 4\%$
CT2000	0.700	3.3	9.234	0. 00181	0.37	2.0	7.9
CT2000	0.700	5.5	9.190	0.00214	0.37	1.9	7.6
CT700	0.720	3.3	6.924	0.00212	0.35	2.1	8.3
CT700	0.720	5.5	6.890	0.00227	0.35	2.2	8.5
CT800	0.750	3.3	7.542	0.00197	0.34	2.0	8.0
CT800	0.750	5.5	7.515	0.00206	0.34	2.2	8.4
CTX	0.556	3.3	7.705	0.00249	0.46	2.1	8.3
CTX	0.556	5.5	7.573	0.00257	0.46	2.3	8.8

implemented as a user-friendly computer program for each of our split-post resonators.[13,14]

For our measurements of low temperature co-fired ceramic substrates we used two split-post dielectric resonators. At room temperature, one resonator had resonant frequency of 3.3 GHz and the unloaded Q-factor of 23250, while the other structure has f_o of 5.5 GHz and Q_o of 12250.

The measurement system used for the microwave characterisation of the LTCC materials is shown in Fig. 2. The system consisted of Network Analyser (HP 8722C), closed cycle refrigerator (APD DE-204), temperature controller (LTC-10), vacuum Dewar, a PC and the split-post dielectric resonator in transmission mode (as discussed above).

To measure Q_o-factor of the SPDR we used very low coupling of the resonator to the external circuitry and applied the approximation

$$Q_o \approx Q_L. \tag{3}$$

To obtain precise values of the Q_L-factor of the split-post resonator and hence accurate values of tanδ of LTCC substrates we have measured 1601 values of S_{21} parameter around the resonance and processed measured data sets using recently developed the Transmission Mode Q-Factor Technique.[15,16]

The TMQF technique involves fitting of an ideal Q-circle to the measured data and a phase correction that removes effects of noise, non-calibrated measurement cables, connectors, coupling structures, cross-talk between the coupling loops, and impedance mismatch from the measured data.

The TMQF is especially useful in cryogenic measurements since they are typically done in the transmission mode, and the measurement systems contain cables and connectors that are difficult to calibrate. As our tests were performed with very low coupling coefficients β_1 and β_2, a modified version of the fundamental relationship of the TMQF technique[14] was used for the Q-circle fitting of measured S_{21} data sets in the TMQF software, namely as:

$$S_{21} = \frac{2R_c Y_{\mathrm{ex1}} Y_{\mathrm{ex2}}}{G_o(1+\beta_1+\beta_2)\left(1+j2Q_L\dfrac{\omega-\omega_L}{\omega_L}\right)} \cong \frac{2R_c Y_{ex1} Y_{ex2}}{G_o\left(1+j2Q_L\dfrac{\omega-\omega_o}{\omega_o}\right)} \tag{4}$$

where G_o is the conductance of an ideal resonator, R_c is the characteristic impedance of measurement system, Y_{ex1} and Y_{ex2} are the external admittances including the coupling losses and reactance, ω_o and ω_L are unloaded and loaded resonant frequencies respectively.

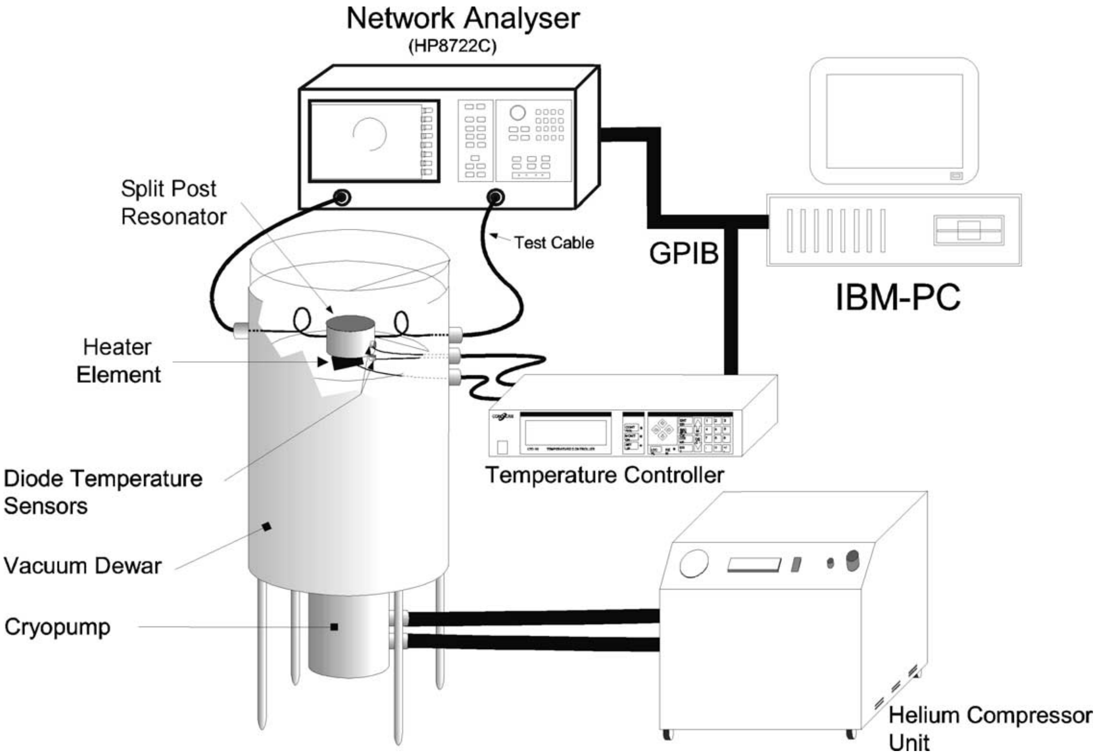

Fig. 2. Experimental set-up to measure the Q_o-factor and f_o of LTCC SPDR.

The accuracy of the TMQF is better than 1% for practical measurement ranges and is applicable to a relatively wide range of couplings. The range of Q-factors measurable is from 10^3 to (10^7).[15,16]

Measurements of low temperature co-fired ceramics from four differing processes as described Section 2 were conducted at room temperature at frequencies of 5.5 GHz and 3.3 GHz using two split post resonators. Temperature dependences of the real relative permittivity ε_r and loss tangent were measured using the 3.3 GHz SPDR in the temperature range from −33 °C to 22 °C.

For variable temperature measurements S_{21} data sets were measured first for the empty resonator and then for the resonator with a given LTCC sample. The TMQF technique was then used to obtain f_o and Q_o values of the empty split-post resonator and of the resonator with the LTCC sample, at exactly the same temperatures. The microwave parameters ε_r and tanδ were computed using the software[13,14] from the resonant frequencies and unloaded Q_o-factors.

To access accuracy of our measurements we performed the uncertainty analysis of measured parameters ε_r and tanδ. The random relative uncertainty in the real part of relative permittivity, $\Delta_r\varepsilon_r$, was calculated using software[13,14] assuming 3-μm uncertainty in the LTCC samples' thickness. This assumption was based on precise measurements of thickness variations across the samples. The $\Delta_r\varepsilon_r$ was found to be below 0.5% for both split post dielectric resonators. The random relative

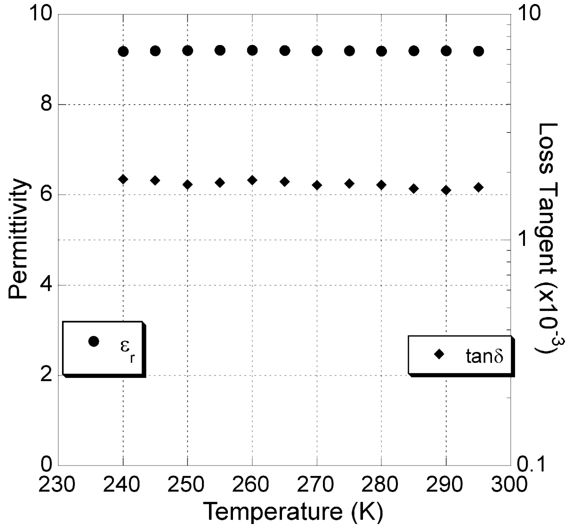

Fig. 3. Real relative permittivity and loss tangent of LTCC samples (CT2000) at 3.3 GHz.

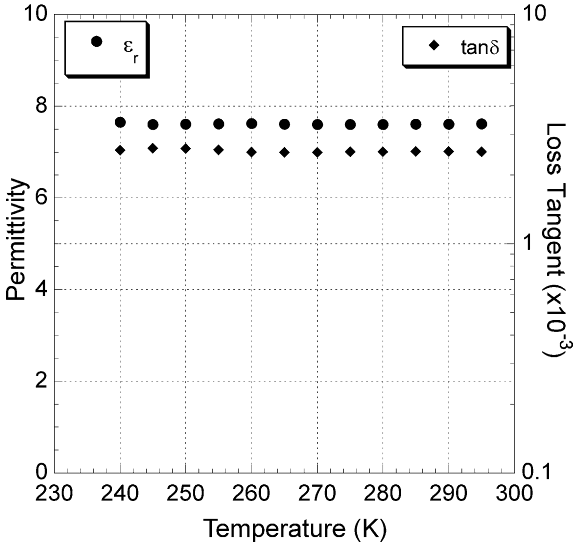

Fig. 4. Real relative permittivity and loss tangent of LTCC samples (CTX) at 3.3 GHz.

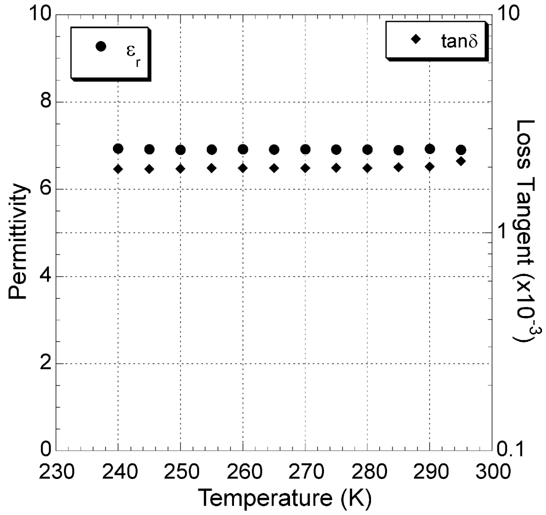

Fig. 5. Real relative permittivity and loss tangent of LTCC samples (CT700) at 3.3 GHz.

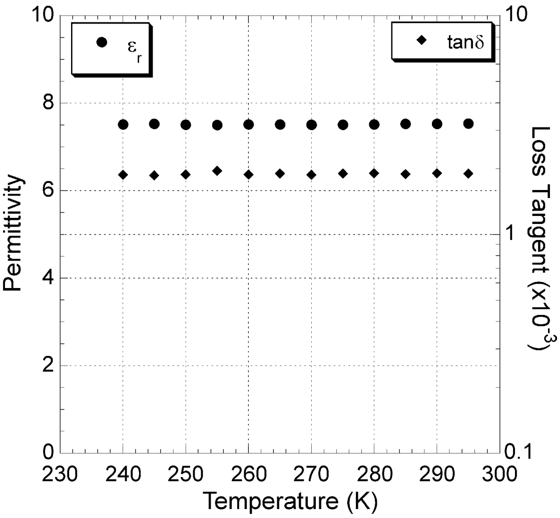

Fig. 6. Real relative permittivity and loss tangent of LTCC samples (CT800) at 3.3 GHz.

uncertainty in loss tangent, $\Delta_r\tan\delta$, was calculated to be at most 2.5% using the same software and assuming 1% random uncertainty in the Q_o-factor values. The absolute uncertainty in $\tan\delta$ has been assessed to be maximum 8.8 for 4% absolute uncertainty in measured Q_o-factor values.

4. Microwave properties of LTCC materials at frequency of 3.3 and 5.5 GHz

Measured temperature dependences of loss tangent and real relative permittivity of the low temperature co-fired ceramics from 240 to 295K at a frequency of 3.3 GHz are shown in Figs. 3–6. A summary of room temperature values of ε_r and $\tan\delta$ at two frequencies as well as calculated measurement uncertainties (as discussed in Section 3) are presented in Table 1.

5. Conclusions

We have shown precise measurements of real part of relative permittivity and loss tangent of four types of low temperature co-fired ceramics. The measurements were performed using two split post dielectric resonators for temperatures varying from 240 to 295K. The tested LTCC samples exhibited ε_r values of 9.2, 7.65, 7.5 and 6.9, independent on temperature from 240 to 295 K at 3.3 GHz. Measurements at 5.5 GHz showed slightly smaller values of ε_r.

The loss tangent of LTCC samples was 0.0018, 0.00249, 0.00212 and 0.00197 at 3.3 GHz and increased to 0.00214, 0.00257, 0.00227 and 0.00206 respectively at 5.5 GHz. The CT2000 samples exhibited the smallest loss tangent of four types of LTCC materials tested. The dependence of $\tan\delta$ showed either a very slight decrease (CT2000 and CTX), no change (CT800) or very slight increase (CT700) from 240 to 295 K.

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References

1. Mandai H., Wakino K. and Nakajima N. Recent development on materials for multiplayer ceramic microwave devices, APMC2001 SMMM, 2001, Taipei, Taiwan, 142–145.
2. Valant M., Glass-free materials for LTCCC technology, 2001, APMC2001 SMMM, 2001,Taipei, Taiwan, 6–11.
3. Barnwell P., Free C., and Tian Z. Low temperature co-fired ceramics (LTCC) and thick film technologies for microwave applications to 70GHz, 2001, APMC2001 SMMM, 2001,Taipei, Taiwan, 1–4.
4. Barnwell P., Free C., Chen L., Aitchison C. A Novel thick film on ceramic microwave technology, APMC'98, 1998, Yokohama, Japan, 495–498.
5. DelaBalle, J., Guillon, P. and Garault, Y., Local complex permittivity measurements of MIC substrates. *AEU Electronics and Communication*, 1981, **35**, 80–83.
6. Krupka, J. and Maj, S., Application of the $TE_{01?}$ mode dielectric resonator for the complex permittivity measurements of semiconductors. *CPEM '*, 1986, **86**, 154–155.
7. Nishikawa, T. *et al.*, Precise measurement method for complex permittivity of microwave substrate. *CPEM '*, 1988, **88**, 154–155.
8. Krupka, J., Geyer, R. G., Baker-Jarvis, J. and Ceremuga, J., Measurements of the complex permittivity of microwave circuit board substrates using split dielectric resonator and reentrant cavity techniques. In *DMMA96 Conference,* 1996, Bath, UK, pp. 21–24.
9. Krupka, J., Gregory, A. P., Rochard, O. C. and Clarke, R. N., Le split resonator et d'autres techniques de mesures. In *Int. Conf. 6-emes Journees de Caracterisation Micro-ondes et Materiaux (JCMM'2000), 2000, Paris..*
10. Krupka, J., Clarke, R. N., Rochard, O. C. and Gregory, A. P., Split Post Dielectric Resonator technique for precise measurements of laminar dielectric specimens—measurement uncertainties. In *XIII Int. Conference MIKON'2000,* 2000, Wroclaw, Poland, pp. 305-308.
11. Krupka, J., Gabelich, S. A., Derzakowski, K. and Pierce, B. M., Comparison of split post dielectric resonator and ferrite disc resonator techniques for microwave permittivity measurements of polycrystalline yttrium iron garnet. *Meas. Sci. Technol.*, 1999, **10**, 1004–1008.
12. Krupka, J., Gregory, A. P., Rochard, O. C., Clarke, R. N., Riddle, B. and Baker-Jarvis, J., Uncertainty of complex permittivity measurements by split post dielectric resonator technique. *J Europ. Ceram. Soc.*, 2001, **21**, 2673–2676.
13. Krupka J., software REZ30.
14. Krupka J., software REZ337.
15. Leong K., Precise measurements of surface resistance of HTS thin films using a novel method of Q-factor computations for Sapphire Dielectric resonators in the transmission mode. PhD thesis, 2000 James Cook University.
16. Leong K., Mazierska J., Precise measurements of the Q-factor of transmission mode dielectric resonators: accounting for noise, crosstalk, coupling loss and reactance, and uncalibrated transmission lines. In *IEEE Tran. Microwave Theory and Techniques*, 2002, vol. 50(9), 2115–2127.