

## Introducing DuPont™ GreenTape™ 9K5 Low Dielectric Constant, Low Temperature Co-Fired Ceramic (LTCC) Tape System

Deepukumar M. Nair \*, James Parisi, K.M. Nair, Mark McCombs, Michael Smith, Elizabeth Hughes, Ken Souders, Anthony Orzel, Bradley Thrasher, Stephen C. Beers, J.C. Malerbi, Scott Gordon

DuPont Microcircuit Materials

14 TW Alexander Drive, Research Triangle Park, NC, 27709

### ABSTRACT

Low Temperature Co-fired Ceramic (LTCC) material systems have been successfully used in microwave and millimeter wave systems for several years. LTCC has very low dielectric loss, high reliability due to inherent hermeticity; high interconnect density, multilayer processing capability leading to true 3D packaging, and better cost-performance balance. While the medium range dielectric constants (7.00 – 8.00) offered by current tape systems have advantages, it is generally difficult to realize high speed systems and efficient antennas on LTCC, especially at millimeter wave frequencies. The difficulty arises from the reduced signal propagation velocity in high-speed applications, and lower radiation efficiency for antennas, both due to higher dielectric constant. To enable and extend applications of LTCC technology to these subsystems, DuPont has developed a new low dielectric constant LTCC system – DuPont™ GreenTape™ 9K5 - which has a dielectric constant of 5.80 (at 10 GHz) that is compatible with the commercial DuPont™ GreenTape™ 9K7 LTCC System. This is achieved without compromising excellent microwave loss properties of the 9KX GreenTape™ platform. These materials systems enable high-speed, high reliability applications while also realizing efficient antennas on LTCC. This paper presents initial characterization of the new DuPont™ GreenTape™ 9K5 LTCC system consisting of low K dielectric tape, gold and silver conductors to evaluate the effects of chemistry, processing conditions, processing latitude, microstructure, and microwave performance. Test coupons with various transmission and resonating structures are designed, fabricated, and tested for the evaluation of transmission losses and dielectric properties. Stability of the material system over multiple re-fire steps is also examined

Key Words: GreenTape™ 9K5, LTCC, microwave characterization, GreenTape™ 9K7, Dielectric characterization.

### I. INTRODUCTION

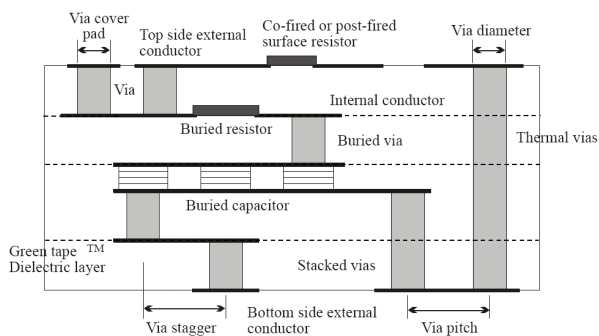
Frequencies of operation for commercial and military microwave systems are on a continuous migration to microwave and millimeter wave ranges due to ever increasing performance requirements and limited spectrum availability. Automotive radars with varying functionality like line departure warning (17/24 GHz), automatic cruise control (77 GHz) and 60 GHz wireless networking are all examples of recent applications which uses microwave and millimeter wave bands that used to be the traditional realm of military hardware. Key challenges facing designers of such systems include the need to achieve the delicate balance between performance – electrical, mechanical, and reliability – and cost. Even for military hardware the relentless march to achieve

lower cost without sacrificing performance is under way.

Low loss signal transmission, high reliability chip attach, and the ability to support antennas are key functional requirements for any microwave/millimeter wave packaging platform. For a specific dielectric material the capability to provide a very stable structural platform, very good dimensional control and stability, the ability to support extremely low loss signal transmission, low susceptibility to temperature and humidity, a suitable range of metallization options, and a range of dielectric constants are essential requirements.

Low Temperature Co-fired Ceramic (LTCC) has been one of the key technologies of choice for microwave and millimeter wave packaging applications for several years. Some of the enabling characteristics of LTCC technology that make it well

suites for microwave/millimeter wave packaging applications are, 1) very stable dielectric properties (with frequency, temperature etc.), 2) very low dielectric loss, 3) range of dielectric constants spanning between those of organic laminates and homogeneous ceramics such as Alumina, 4) Lower processing/firing temperature requirements compared to High Temperature Co-fired Ceramics (HTCC) which enables the use of noble metallic conductors (Gold/Silver) resulting in further reduction of overall interconnect signal losses, 5) multilayer capability enabling true 3 dimensional routing and packaging capability, 6) excellent CTE (Coefficient of Thermal Expansion) match to MMIC (Microwave/Millimeter wave Integrated Circuits) material systems such as GaAs (Gallium Arsenide)/SiGe (Silicon Germanium)/GaN (Gallium Nitride) etc. 8) very low/non-existent water penetration resulting in true hermetic packages leading to very high reliability packaging platform with excellent electrical performance, 9) high routing density, and 10) an order of magnitude better thermal conductivity compared to organic laminate materials [1-3].



**Figure 1: Typical LTCC Circuit**

Generally, LTCC material systems are heterogeneous composites of ceramic fillers and various specialty glasses along with organic binders. Specially formulated thick film conductor compositions are used to form signal traces and other features on the dielectric. The green dielectric is tape-casted to form individual layers of dielectric, vias are punched, circuit features are screen printed on each layer and layers are collated and laminated together after inspection and testing to form the green multilayer circuit. The green laminate is then fired at elevated temperatures (800 to 1000<sup>0</sup> C) and for duration of time (3 to 30 hours) to form a monolithic ceramic multilayer circuit. The specific process conditions and firing profile are selected according to the particular LTCC system chosen. A typical LTCC circuit structure is shown in figure 1.

## II. GreenTape™ 9K5 LTCC

There are several commercial DuPont™ GreenTape™ LTCC Systems – mainly 951 and 9K7 available today. Both of these DuPont GreenTape™ systems were designed to be compatible with gold, silver, or gold-silver mixed metal co-fired conductor traces for use in automotive, consumer, aerospace, and military applications. The DuPont GreenTape™ 951 System continues to be the industry standard of commercial LTCC systems, and it is used for many general purpose applications that operate below 20 GHz. The DuPont™ GreenTape™ 9K7 System was introduced in 2009 and is comprised of low loss glass-ceramic dielectric that is designed for applications operating at higher frequencies. All DuPont™ GreenTape™ LTCC systems are fully compatible with standard packaging process such as soldering, wire bonding, brazing etc.

A range of available dielectric constants within the material system is highly desirable for realizing optimized system level designs. Inherently, a material with higher dielectric constant will enable the reduction of overall circuit size in general, and achieves high routing density of interconnects in particular. This is because the interconnect geometry scales inversely with the square root of wavelength. In addition, higher dielectric constant will force a higher percentage of electric field to be confined to the substrate thereby reducing the crosstalk and electromagnetic emission related signal integrity problems which enables closer spacing between signal conductors. The combined effect of geometrically smaller lines spaced closer results in size reduction of the circuit. On the other hand, as the substrate dielectric constant reduces line geometry dimensions increase and the spacing required between them also increases; making the circuit larger. Smaller Ground-Signal-Ground impedance controlled pad geometry can also be realized on higher dielectric constant materials to match the ever-decreasing MMIC bump pitches; which is a significant advantage in packaging millimeter wave MMIC using flip chip technology.

While a higher dielectric constant packaging substrate provides significant advantages in terms of circuit size; it becomes increasingly difficult to fabricate high efficiency printed microstrip antennas on such substrates. For higher antenna efficiencies; a significant – 100% in the ideal case of unity efficiency – percentage of the electric field needs to be released from the substrate material and radiated in to the atmosphere. Higher dielectric constant will

tend to force most of the field within the substrate there by reducing the radiation efficiency. Another factor that further reduces the efficiency is the smaller antenna patch size when higher dielectric constant substrates are used, which directly affects the aperture of the antenna. Such limitations will become more pronounced and difficult to tackle at millimeter wave frequencies. There are some clever ways of fabricating antennas on high dielectric constant reported in the literature over the years [4-6]. However, these involve cutting cavities under the antenna patches, inserting low dielectric constant materials within the high K substrate etc. All of these techniques require tedious and cumbersome processing and/or the use of exotic materials. By far, the simplest means to achieve the required antenna efficiencies is to use a low dielectric constant material. Since the ability to support high efficiency antennas is a critical requirement for a material system which offers a complete packaging platform – namely, high reliability, high density interconnects, as well as high efficiency antennas simultaneously – the choice of dielectric constant is very critical. In addition, there exists a delicate balance between the magnitude of dielectric constant and acceptable dielectric loss as well. GreenTape™ 9K5 system is the result of DuPont's effort to find such balance between all critical microwave/millimeter wave packaging requirements.

Since LTCC systems are composites of Alumina and glasses, their dielectric constant values range between 5.9 and 8.50 for commercially available systems. Recently, DuPont has developed a new LTCC material system – GreenTape™ 9K5 - which is designed to have properties suitable for microwave/millimeter wave system packaging. The dielectric constant of 9K5 is 5.80 and loss tangent is 0.001 at 9.5 GHz. The development of this system significantly extends the range of dielectric constants available within DuPont™ GreenTape™ LTCC portfolio. This paper describes the methods and results on characterizing this new system. Both dielectric properties and various transmission line performance parameters are evaluated within the scope of the work described herein. First part of the paper describes the fundamentals of the 9K5 material system, followed by dielectric data from split cavity testing. Second part provides the details of the microwave test coupon used for transmission line testing and resonators used for dielectric characterization along with test results.

### III. GreenTape™ 9K5 CHEMISTRY

The 9K5 LTCC is a glass ceramic-ceramic composite system and is based on a proprietary crystallizable glass with added ceramic fillers. On heat treatment, the glass will partially crystallize and react with fillers to give the LTCC a random composite of glass ceramic-ceramic-“remnant” glass with several crystal species within the microstructures. The presence of several crystal structures within the fired LTCC reduces preferential crystal growth. Additional crystal growth after the initial firing is kept to a minimum due to the reduced amount of “network” modifying ions in the “remnant” glass. The so-called glass “network-forming” and “network modifying” ions and the selection of the physical characteristics of the frit and filler powders are designed in such way as to reduce the surface roughness of the fired LTCC. This lack of additional crystal growth keeps the surface roughness to a minimum through six 850°C re-fires.

The wetting characteristics of the “remnant glass” allow the glass to wet the ceramic surfaces; yielding a well sintered ceramic body. The interaction of the filler with the remnant glass gives additional modification of crystal chemistry of the crystalline materials modifying the dielectric properties of the LTCC.

The dielectric tape is designed such that the viscosity of the “remnant” glass remains high when fired at the 850°C processing temperatures. This controls any unwanted interactions between the tape ingredients and the conductor/resistor binder systems. Table I illustrates a summary of the X-ray diffraction analysis of 9K5's fired tape surface after the initial firing at the 26.5 hour box furnace profile. Also included in the table are the chemical analysis results for parts re-fired for an additional ten times at an 850°C/30 minute belt furnace profile. Details of the chemical composition are shown in Table I.

**Table I: Chemical composition of 9K5**

OVERALL COMPOSITION	CoF	1X	3X	6X	10X
*Amorphous Material (%)	27	26	27	27	26
*Crystalline Material (%)	73	74	73	73	74
CRYSTALLINE COMPOSITION	CoF	1X	3X	6X	10X
Formulated Crystal A (%)	76	75	76	76	76
Glass Derived Crystal B (%)*	1	2	1	1	1
Glass Derived Crystal C (%)*	3	3	3	3	3
Glass Derived Crystal D (%)	15	14	14	15	15
Glass Derived Crystal E (%)	5	6	6	5	5

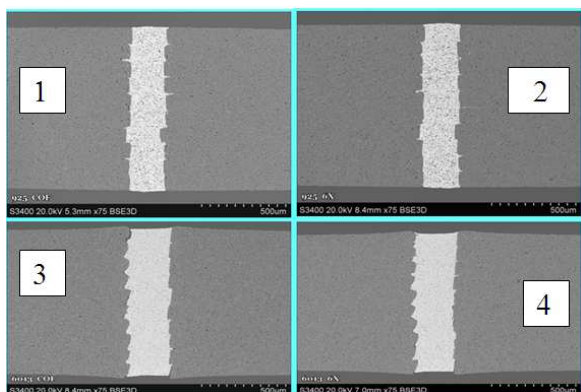
\* Glass reaction derived crystal

The X-ray diffraction results indicate the presence of five different crystal species of the

dielectric following the initial fire; these crystals are either from the partial crystallization of the glass and/or the result of the interaction of fillers with original glass and/or reaction results of fillers and “remnant” glass. Examination of the data shows there is no significant difference in the quantity of each crystal species between initial fire and 10x re-fired parts. These results show that the crystallization of glass and filler-glass and filler-“remnant glass” interactions are completed at the initial firing and the system reached an equilibrium state and no further increase in the amount or change in the chemistry of crystals with re-fires. This also indicates that the amorphous “remnant” glass is in a stable glass structure and further interaction with conductor/resistor binders is unlikely to occur with re-fires.

### Conductor Compatibility:

Following micrographs are the (1) stacked gold conductor after co-fire (2) gold conductors after 6 re-fires (3) stacked silver conductor after co-fire and (4) silver conductor after six re-fires along with corresponding LTCC microstructures. These microstructures show no significant grain growth after co-fires, and that the LTCC structure is stable. The ten stacked vias of gold and silver conductors show excellent conductor compatibility to LTCC, showing good ceramic-conductor interface bonding and excellent bonding between layers of vias.



**Figure 2: SEM: Stacked via with different metallizations**

### IV. 9K5 TEST COUPON

The purpose of the test coupon is to evaluate the microwave properties of transmission lines fabricated on 9K5 substrate. In addition, ring resonators and T resonators are also included on this test coupon for in-circuit dielectric characterization the material system. All test structures are carefully

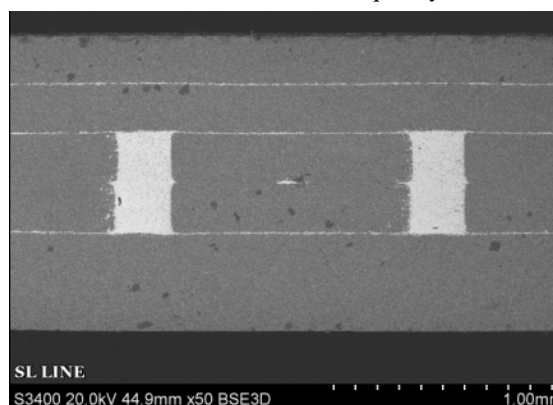
designed, simulated, and optimized with a 2.5 D Method of Moments simulator Sonnet [7] and a 3 D Finite Element Method based simulator HFSS [8]. The same test coupon layout was fabricated with both silver and gold metallizations.

The test coupon is built with six individual layers of 0.250 mm thick each. Top layer of the coupon is used for various microstrip test structures – microstrip lines of varying lengths, micro strip ring and T resonators, and microstrip TRL calibration lines and CPW (Co-Planar Waveguide) transmission lines. There is a solid ground plane one layer below making the reference ground for both microstrip and CPW structures 0.250 mm vertically below the top layer. Third metal plane is used as the top ground for Stripline test structures comprising of Stripline transmission lines, T resonators, and Ring resonators. Fourth metal layer from the top is used as the signal layer for Stripline test features and the fifth metal layer is the bottom ground plane. Top and bottom ground planes of the stripline layers as well as that of the CPW structures are electrically connected using vias as necessary. An SEM image showing the crosssection view of the fabricated test coupon is shown in Figure 3

### V. DIELECTRIC CHARACTERIZATION

#### Split Cylinder Cavity Method

We used a split cylindrical cavity resonator for bulk dielectric property measurements [9]. The cavity is designed to have a fundamental resonance frequency of 9.50 GHz and is connected in series to the S parameter test loop of a Vector Network Analyzer (VNA) so that its transmission properties can be measured as a function of frequency. This test



**Figure 3: 9K5 Test coupon cross section SEM**

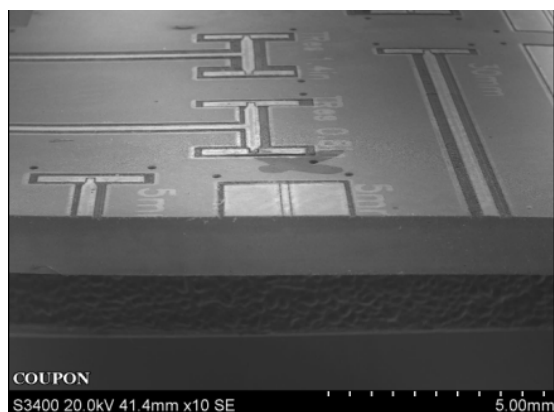


Figure 4: 9K5 Test coupon SEM : Transmission lines

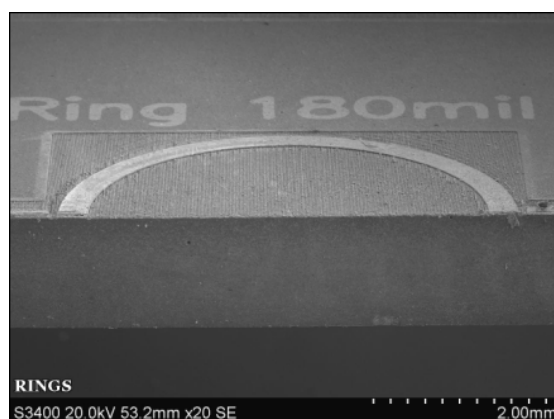


Figure 5: 9K5 Test coupon SEM: Ring Resonator

set up is developed over many years and is proven to be highly accurate. Our particular test set up is highly repeatable and reproducible with a gage R&R of 6.4 % and is maintained under continues calibration as per ISO 9000 standards. LTCC materials under test is formed to have 2.1 mm per layer thickness and four individual layers are laminated together and fired to form a single test coupon. A batch of six coupons is prepared simultaneously under highly controlled process conditions. Thickness of each of these coupons are measure using a highly accurate ( $\pm 2$   $\mu\text{m}$ ) LVDT based automated thickness measurement system. The accuracy of thickness measurement is a critical requirement for accurate characterization of dielectric properties with this method. 2-Port scattering parameters (S-parameters) as a function of frequency are measure for the empty cavity as well after inserting the test coupon. From the shift in transmission resonance peak and changes in bandwidth and hence the quality factor, the

dielectric constant and loss tangent can be accurately measured. Table 1 shows the dielectric properties measured for 9K5 samples under test.

Table II: Dielectric Properties of GreenTape™ 9K5 Split Cavity (un-metalized) method (9.50 GHz)

Sample	dK	Loss Tan
1	5.82	0.0015
2	5.82	0.0014
3	5.80	0.0015
4	5.79	0.0015
5	5.80	0.0016
6	5.82	0.0015
<b>Average</b>	<b>5.81</b>	<b>0.0015</b>
<b>Std.Dev.</b>	<b>0.01</b>	<b>0.0001</b>

From the data provided in Table II it is clear that the bulk dielectric constant of 9K5 averages around 5.81 with a very tight distribution as evident by the standard deviation of 0.01 and the loss tangent is 0.0015 with standard deviation 0.0001 at 9.5 GHz. These dielectric properties put 9K5 among the best LTCC materials in the market today.

#### In-Circuit Dielectric Characterization – Printed Resonators:

Note that the split cavity method while very accurate, repeatable, and reproducible has two drawbacks. 1) It provides dielectric data only at one frequency, 2) dielectric properties obtained are that of the bulk LTCC material and it does not take in to account any influence the presence of thick film metallizations may have on both dielectric constant and loss tangent. A priori knowledge of the dielectric properties at the design frequency range – not just one frequency – is critical in realizing successful designs with minimum number of iterations during the design phase. Also, since any circuit application will require the presence of metallizations on the material, the knowledge of any potential change in dielectric constant in the presence of metallization is critical for design success as well. Ring resonators and T resonators are two commonly used resonant circuits to extract dielectric constant over a wide range of frequencies. Several microstrip and stripline ring resonators were designed and fabricated on the test coupon. The radii of the rings were selected so as to have the fundamental resonance at 5 GHz and 10 GHz each. Transmission parameters ( $S_{21}$ ) for a microstrip ring with mean radius of 2.49 mm is

shown in figure 6 and that for a stripline ring resonator with radius 3.35 mm are shown in figure 7.

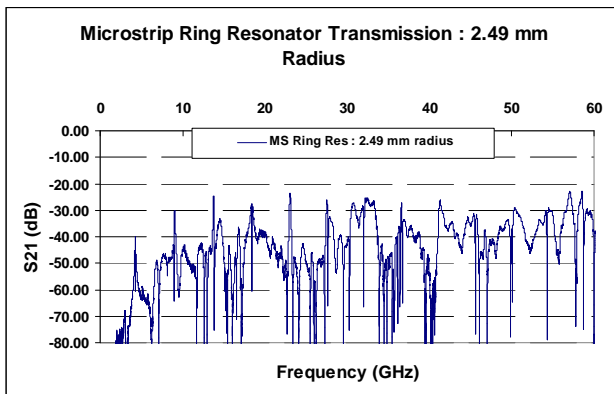


Figure 6: Microstrip Ring Resonator (2.49 mm radius) – Transmission response

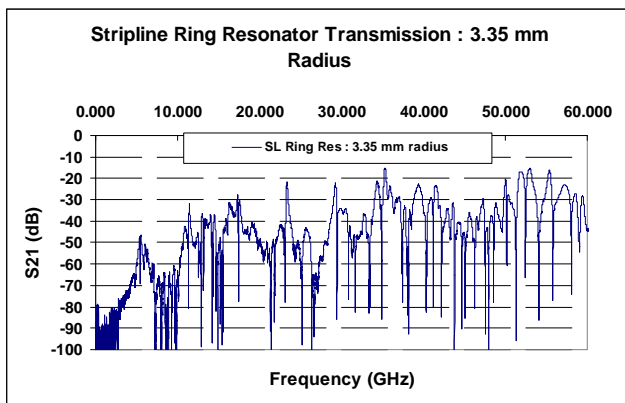


Figure 7: Stripline Ring Resonator (3.35 mm radius) – Transmission response

Table III: Dielectric constant extracted from Stripline and Microstrip Ring Resonator transmission data

Order of Resonance	Resonant Freq (GHz)		Dielectric Constant	
	SL Ring	MS Ring	SL Ring	MS Ring
1	5.91	4.71	5.82	5.64
2	11.82	9.44	5.82	5.62
3	17.74	14.16	5.81	5.62
4	23.68	18.79	5.80	5.67
5	29.59	23.29	5.80	5.78
6	35.44	27.87	5.82	5.82
7	41.47	32.32	5.79	5.89
8	47.48	36.83	5.77	5.93
9	52.82	41.37	5.90	5.95
10		45.76		6.01
11		50.36		6.00
12		54.41		6.13

Dielectric constant was exacted from the resonant frequencies as per the mathematical treatment outlined in Reference [10, 11]. Table III shows the resonant frequencies and corresponding

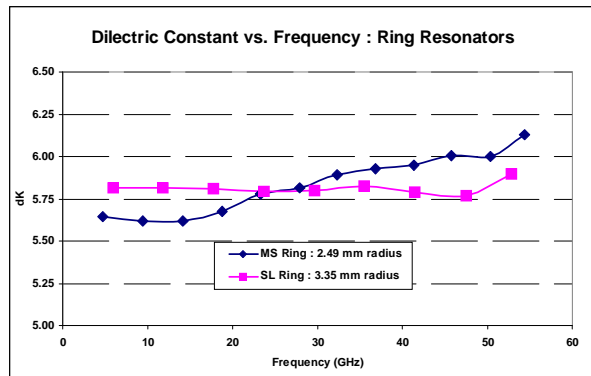


Figure 8: Microstrip Ring Resonator (2.49 mm radius) – Transmission response

dielectric constants for both microstrip (2.49 mm mean radius) and the stripline ring resonators (3.35 mm). Figure 8 shows the dielectric constant as a function of frequency for these two cases. The graph also shows the split cavity value of dielectric constant obtained for unmetallized bulk samples at 9.50 GHz

It is interesting to note that the dielectric constants obtained from the strip line resonators are much more stable than those from microstrip rings. The reason for this is the dispersion inherent in microstrip structures. In a microstrip circuit the electric field is distributed between the dielectric and surrounding air. Specific configuration of the conductor geometry – line width, conductor thickness etc. – has a significant influence in the field distribution. Also, the field distribution is highly frequency dependent (dispersion). The parameter that defines the resonant behavior is an effective dielectric constant rather than the actual dielectric constant of the dielectric. The fundamental resonance equation used to extract dielectric constant from resonant frequency yields the effective dielectric constant and empirical equations with limited validity are used to arrive at the dielectric constant of the substrate material and hence the frequency dependence of dielectric constant is somewhat exaggerated in the case of microstrip resonators.

On the other hand, for a stripline circuit the resonator is fully enclosed by the top and bottom ground planes and the electric field is distributed entirely in the dielectric material under test. Fundamental resonance equation directly yields the material dielectric constant unlike in the case of microstrip resonator where it yields only the effective dielectric constant. Hence, the frequency dependence of measured dielectric constant will be significantly

lower in the case of stripline resonators compared to microstrip resonators. Dielectric test data obtained for 9K5 and shown in figure 8 and table III confirm this hypothesis. In addition, the dielectric constant obtained by the stripline resonator will be more representative of the actual material property.

However, it is still important to investigate dielectric constant using microstrip resonators from a circuit application point of view since microstrip circuits form a very significant part of any system design. So it is important to understand the dielectric constant *as seen by* the given microstrip circuit configuration to ensure design success.

### VI. TRANSMISSION LINE PERFORMANCE

All three major type of transmission lines – Microstrip, CPW, and Stripline – are tested up to a frequency of 40 GHz. The test frequency is limited to 40 GHz since an individual dielectric thickness of 0.250 mm is selected in the first phase of testing reported in this article. Higher order modes are excited in the CPW Ground-Signal-Ground probe pads used for measurements above 45 GHz. To suppress these modes and to extend the test frequencies 0.125 mm layer thickness needs to be used. This work is in progress and will be reported subsequently. It is significant to note that the material system itself is not limited in terms of frequency of operation and can be used up to 110 GHz and possibly beyond.

Figure 9 shows a picture of the top layer of the fabricated coupon and various transmission lines used in this work.

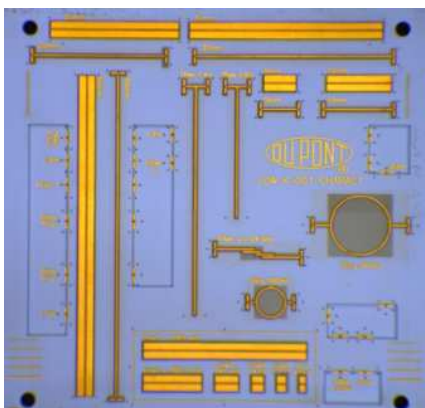


Figure 9: Fabricated 9K5 test coupon (Gold)

Scattering parameters (S parameters) are measured with an Anritsu Vector Network Analyzer and Cascade probe station. Multiple lengths of each transmission line type is measured in the frequency range 10 MHz to 40 GHz. Both return loss and insertion loss are extracted and loss per unit length is calculated. Figures 10 – 14 show the return loss and insertion loss per unit length for various transmission lines. Each graph shows the corresponding parameter obtained from test coupons with both gold and silver metallization.

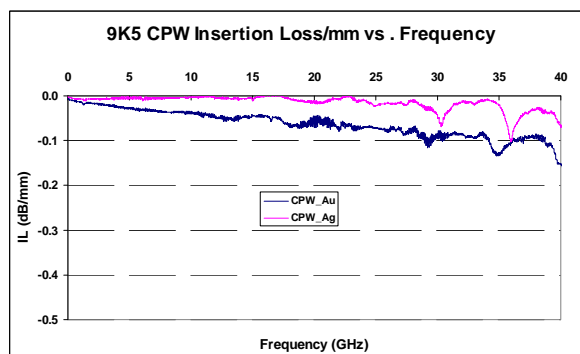


Figure 10: CPW Insertion Loss/mm – Gold and Silver

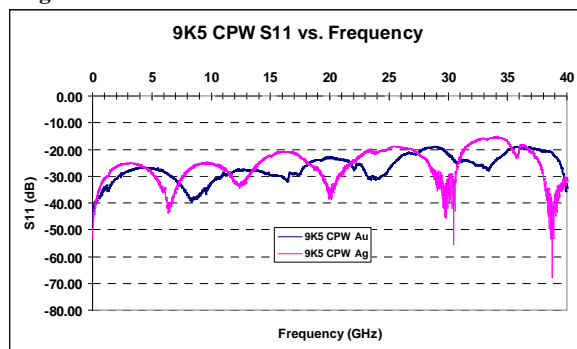


Figure 11: CPW Return Loss – Gold and Silver

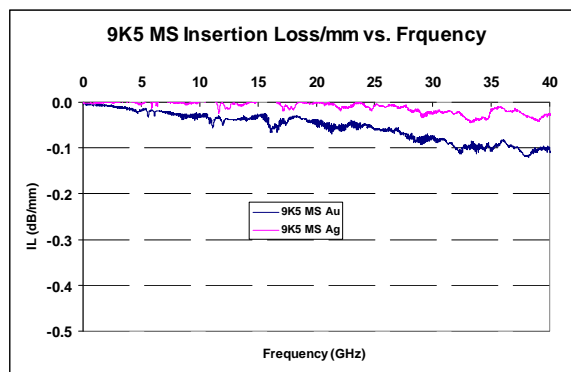


Figure 12: Microstrip Insertion Loss/mm – Gold and Silver

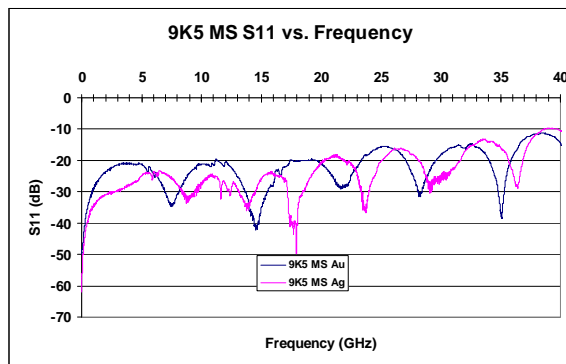


Figure 13: Microstrip Return Loss – Gold and Silver

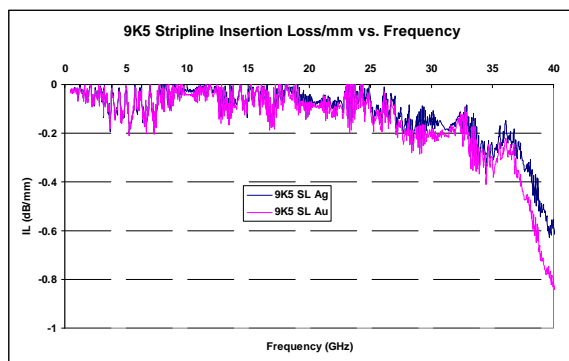


Figure 14: Stripline Insertion Loss/mm – Gold and Silver

From the insertion loss/mm data it is clear that very good signal transmission performance can be achieved on 9K5. Loss through the measurement band (10 MHz to 40 GHz) remains below 0.1 dB/mm for both microstrip and CPW transmission lines. For striplines, loss stays below 0.2 dB/mm up to 30 GHz. This is larger than the loss for microstrip and CPW and is expected since the stripline is enclosed by the dielectric material with a finite loss tangent compared to microstrip and CPW lines where the top side is air (almost no loss). However, losses for the stripline increase significantly between 30 and 40 GHz which is suspected to be due to the G-S-G probe pads to strip line transition.

## VII. REFIRE STABILITY

An LTCC system needs to be able to withstand multiple firing cycles after the initial firing for typical package processes. Heat treatment (lamination, firing etc.) is one of the key processes used in the manufacturing of LTCC circuits.

Table IV: Dielectric Constant and Loss Tangent: Split cylindrical cavity at 9.5 GHz after re-fires (850°C, 30 min)

Part No.	Co-Fire		3 X Re-Fire		6 X Re-Fire	
	dK	Loss Tan	dK	Loss Tan	dK	Loss Tan
1	5.82	0.0015	5.87	0.0019	5.85	0.0019
2	5.82	0.0014	5.87	0.0019	5.85	0.0018
3	5.80	0.0015	5.85	0.0019	5.83	0.0018
4	5.79	0.0015	5.83	0.0019	5.82	0.0019
5	5.80	0.0016	5.85	0.0021	5.83	0.0022
6	5.82	0.0015	5.85	0.0019	5.85	0.0018
Average	5.81	0.0015	5.85	0.0019	5.84	0.0019
Std.Dev.	0.013	0.0001	0.01	0.0001	0.01	0.0001

Since LTCC materials are subjected to elevated temperatures compared to organic laminates – especially during firing at 850°C – it is imperative that their dielectric properties remain unchanged. To establish the stability of GreenTape™ 9K5 tape system, test samples were re-fired six times with each re-fire cycle being 850°C for 30 minutes. Dielectric constant and loss tangent were measured using split cylindrical cavity technique after three re-fires and then after six re-fires. Data from these tests are shown in Table IV. From the data it is clear that the material system is very stable with multiple re-fires indicating that the initial co-fire completes all significant phase transitions resulting in a stable LTCC system.

## VIII. 9K5/9K7 COMPOSITE LTCC

Both the DuPont™ GreenTape™ 9K7 and 9K5 LTCC systems are based on similar materials platform and hence are compatible with each other. Moreover, the same metallizations – both gold and silver – can be used for both material systems. Compatibility of 9K5 with the commercial 9K7 (dK = 7.10, loss tangent = 0.0009) for single composite substrate packaging solutions for Transceivers which require both MMIC interconnections and antennas. By laminating and firing the new 9K5 low K tape layers with very low loss DuPont™ GreenTape™ 9K7 tape layers, one can achieve a single, co-fired, monolithic substrate where 9K7 layers will provide very low loss and high density interconnects for MMIC, while the 9K5 layers will provide a suitable substrate for efficient antennas. Extensive testing is undergoing to establish process conditions for co-processing of 9K5 and 9K7 at the time of preparing this report and results will be published subsequently.

## IX. CONCLUSIONS

DuPont has usefully completed the development of a new lower dielectric constant LTCC tape system to extend the range of dielectric constants available within its GreenTape™ LTCC portfolio. The new tape system – GreenTape™ 9K5 – has a dielectric constant of 5.80 and loss tangent of 0.0015 at 9.50 GHz. Dielectric properties and microwave performance of 9K5 LTCC system were investigated in detail. Dielectric characterization was carried out with un-metalized bulk samples using an industry standard split cylindrical cavity resonator at 9.50 GHz as well as using printed ring resonators in both microstrip and stripline configurations and found to have very good agreement. In addition, frequency dependence of dielectric constant up to 50 GHz is established. Microstrip, Stripline, and Coplanar Waveguide transmission lines were designed, fabricated and S parameters tested up to 40 GHz. Both CPW and Microstrip transmission lines were found to have less than 0.1 dB/mm insertion loss and Striplines have a loss less than 0.2 dB/mm. Transmission line loss data along with low dielectric loss tangent indicate that GreenTape™ 9K5 is a very good microwave quality circuit substrate and is positioned among the best LTCC materials available in the market today. Re-fire stability of 9K5 tape system is also established by conducting dielectric characterization after subjecting test parts to 3 X and 6 X re-fires at 850<sup>0</sup> C for 30 minutes for each re-fire cycle. The data collected over the course of this work establishes DuPont™ GreenTape™ 9K5 as a high quality LTCC system suitable for microwave/millimeter wave applications.

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