Analysis of the Impact of Environmental Conditions on the Reliability in 5G PCB Assemblies

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Abstract

The designs of integrated systems are increasingly compact while the requirements of application, especially in the automotive sector, remain demanding. One main challenge is posed by the environmental conditions. In the present study, their impact on mmWave 5G PCB assemblies is evaluated with respect to both mechanical and high-frequency properties. To that end, material samples were stored at three temperatures for various durations in order to accelerate the ageing effects. Afterwards, the samples were tested by use of mechanical, dielectric and high-frequency test methods. Thermo-oxidative ageing processes were observed and lead to significant changes in mechanical and dielectric properties, with simultaneous changes of sample color. The combined approach of mechanical and high-frequency analysis allows for three innovative advantages: First, a correlation of the degradation in performance with other parameters, e.g. sample change of color, which is much easier to detect. Second, the definition of a Safe Area of Operation and a methodology to estimate the behaviour of a mmWave 5G PCB assembly over its lifetime. Finally, the study opens the pathway to a design for robustness of mmWave communication system in automotive applications.

Keywords—PCB, RF, Robustness, 5G, Warpage, Dielectric, Mechanical, Ageing effects

I. Introduction

The current developments in automotive systems show a strong trend towards increased vehicle-to-vehicle (V2V) and vehicle-to-everything (V2X) communication. The communication systems play a vital role in improving road safety, and lead to optimized traffic flow. V2V communication enables vehicles to exchange information with other (nearby) vehicles in real-time or vehicles connecting to cloud-based platforms to access a wide range of services and applications. The progress is fostered by the promising capabilities of mmWave systems. The mobility of future decades builds heavily on interconnected participants. V2V/V2X communication represents a basic requirement for advanced automotive driver assistances systems, autonomous driving and smart transport systems. As a consequence, Printed Circuit Boards (PCB), as a substrate material for such advanced systems, must provide stable mechanical, electrical and dielectric properties for high and long-term temperature and humidity loadings. Therefore, in the design of such systems different questions arise. First it is of interest, if the PCB material is suitable for the intended use case? To answer this question, it needs to be identified what the lifetime limit of the material is with respect to the intended application conditions. In order to identify the lifetime limit, we need to estimate, what functional properties limit the lifetime and which degradation mechanisms are associated.

Material used in PCBs are laminates based on glass fibres embedded in a polymer matrix of either epoxy or polyimide. Since the materials are subjected to the harsh environmental conditions, a detailed investigation of possible changes in the properties due to the conditions is needed. For example, the exposure to elevated temperatures leads to a degradation in the materials microscopic structure and in turn decreases the mechanical integrity. Finally, the thermomechanical reliability of the laminate is compromised. In addition, a degradation of radio frequency (RF) performance is to be expected. All these changes are referred to as ageing.

It is known, that exposure to high temperature and oxygen loading initiates various chemical and physical processes in the PCB, referred as thermo-oxidative ageing. This process starts with the absorption of oxygen in the polymer, followed by a diffusion process. The oxygen then leads to a reaction, which can cause for example chain scission. The reaction may furthermore lead to a change in colour, as well as alterations in mechanical and dielectric properties. In total, optical properties and thermo-mechanical material parameters (glass transition temperature (T_g), coefficient of thermal expansion (CTE), modulus of elasticity as well as dielectric parameters (permittivity ε_r and losses $\tan\delta$) react sensitively to these ageing mechanisms and can be used for evaluating the ageing resistance [1, 2]. In operation, integrated systems degrade slowly with time. Accelerated ageing tests and lifetime predictions are of crucial importance for the reliability of PCB assemblies, as their long-term performance often requires a lifetime of over 15 years and cannot be tested in laboratories for their actual lifespan.

The controlled accelerated ageing tests furthermore allow for an analysis of the underlying mechanisms. In additions to the direct physical and chemical effects, the temperature loading plays a crucial role in all chemical reactions. An increase of temperature leads to an acceleration of the chemical ageing process. The reaction kinetics can be described by the well-known Arrhenius Equation [3, 4]. This relation is typically modified and used to estimate the time to failure. Because in our case a failure criterion is not defined, we determine the time to degradation (t_d). The equation is being used as follows:

$$t_d = K_0 e^{-\frac{\Delta H}{RT}} \qquad [1]$$

In this equation, the time to degradation, t_d, is described as a function of the temperature T in Kelvin, the relative gas constant R, the activation energy ΔH and a material constant K_0. In order to estimate the constants ΔH and K_0, material samples were aged at different elevated temperatures for specific time intervals, followed by an extensive characterisation, as listed below. A threshold value was extracted, at which significant ageing did occur in order to estimate t_d for each material property. With this results the time until degradation of the material is going to be expected, can be estimated for different application temperatures by simple extrapolation. Therefore, a Safe Area of Operation (time, temperature) can be defined, in which no significantly measurable degradation effects may impact the material behaviour.

II. Experimental and Results

A. Analysed Materials

For the investigations, an RF compatible PCB laminate with low Dk glass fabric and low dielectric losses was chosen. Depending on the respective materials characterisation either an application-oriented layer structure with a total thickness ~900 µm or a single layer of the same material with a thickness of ~300 µm was utilised. The embedded glass fabric provides a high dimensional stability for the PCB and adapts the thermal expansion behaviour to copper. Furthermore, the PCB material is characterized by a relatively high glass transition range (~180°C). The structure of the used multi-layer laminates is shown in **Error! Reference source not found.**. The datasheet values from the supplier are summarized in Table 1.

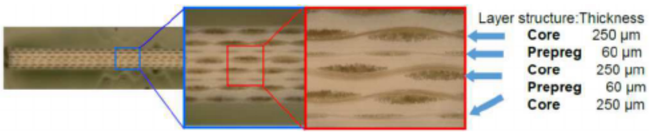


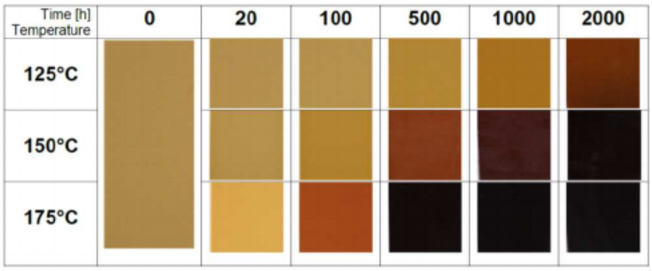
Fig. 1: Structure of used multilayer laminates (total thickness ~900 µm).

TABLE 1: PCB MATERIAL DATA FROM SUPPLIER DATASHEET.

T_g [°C]	CTE (<T_g) [ppm/K]	ε_r at 10 GHz	tanδ at 10 GHz
>185	14...16	3.6	0.004

All samples were stored in temperature chambers under steady-state conditions of 125°C, 150°C and 175°C for defined times of 20h, 100h, 500h, 1000h, 2000h. Visual inspections of the stored sample was conducted, indicating a significant change in color, see Table 2, which is a result of the reaction between the polymer and the oxygen from the environment. As expected, the changes of color on the multilayer PCB materials (substrate surface) exhibited different rates of discoloration, depending on the exposure temperature and time. At 125°C, darkening was observed only after 1000h of storage. In contrast, samples stored at 175°C already exhibited a significant darkening after 100h. Samples stored at 150°C began to darken on the surface after 500h.

TABLE 2: EFFECT OF TEMPERATURE STORAGE ON PCB COLOR.



Time [h] / Temperature	0	20	100	500	1000	2000
125°C						
150°C						
175°C						

The time for a significant change of color on the sample surface from yellow to brown, dependent on storage temperature, is defined as the time to degradation, t_{d_color} and is summarized in Table 3.

TABLE 3: TIME FOR DEGRADATION OF THE SURFACE COLOR.

	Exposed temperature		
	125°C	150°C	175 °C
t_{d_color}	>1000h	>100h	>20h

B. Test methods

In the study, various test methods were employed in order to identify and correlate the material parameters that exhibit sensitivity to the oxidation effects. The choice of test methods was guided by the common parameters of interest for reliability analysis.

TABLE 4: SELECTED PROPERTIES AND RELEVANT TEST METHODS.

Properties	Test method
Coefficient of Thermal Expansion (CTE)	TMA
Glass Transition temperature (T_g)	TMA/DMA
Temperature induced warpage behaviour	Warpage analyzer
Permitivity ε_r, dielectric loss factor tan δ (non-metallised)	Split-Cylinder Resonator
Permitivity ε_r, dielectric loss factor tan δ (with Cu layer)	Planar resonators
RF performance	Single element patch antenna

The thermo-mechanical analysis (TMA) method, the dynamical mechanical analysis (DMA) method and the warpage analysis method of the aged samples were used to determine the thermo-mechanical material parameters depending on temperatures and storage time. On the other hand, the dielectric properties of aged samples, the permittivity ε_r and the losses tanδ were characterized by means of dielectric analysis. The permittivity describes the amount to which a material can be polarized by an electric field and the losses describe the dissipated energy which occurs during the process of changing the polarization of the materials in an alternating field. For any RF circuit, the permittivity is a crucial parameter since it is one factor that defines the impedance of transmission lines and other interconnects. A change in ε_r will lead to a change in impendence of a line and hence a mismatch in the signal path, resulting in additional reflections. Furthermore, the performance (e.g. resonance frequency) of components will be affected by a change in ε_r.

The value of tanδ determines the percentage of RF power which can be transmitted or radiated in a system with respect to the signal source. An increase in tanδ will lower the available power for the intended operation. A system which uses a lossy dielectric material will require more active components for amplification in order to achieve sufficient functionality. In order to limit the number of active components, RF systems usually employ low loss dielectric substrates and as short as possible transmission lines between signal source and e.g. antenna.

C. Thermo-Mechanical Parameters

a) Thermomechanical Analysis (TMA) for determination of CTE and Tg

The glass transition range, indicated by the glass transition temperature (T_g) marks the division between rubbery and glassy behaviour for polymer materials. At T_g a change of slope of specific volumes respectively length versus temperature exists.

It can be exemplarily shown that the storage temperature of 150°C up to 100h does not significantly change the linear thermal expansion coefficient (below T_g) and the T_g. Only for longer exposure times, the expansion coefficient decreases and the glass transition temperature increases noticeably. These changes in thermal properties can likely be attributed to the influence of the thermo-oxidative degradation process in the polymer matrix. It was assumed that with longer storage times, a decrease in adhesion between the polymer matrix and glass fabric takes place. Since the glass fabric has a much higher stiffness and lower expansion behaviour, this reduction in adhesion leads to a significant shift of the glass transition temperature towards higher temperatures. Further investigations (e.g. DSC) are necessary to confirm this. These changes in thermal expansion behaviour occur earlier (accelerated) at storage temperatures of 175°C and later at 125°C [5].

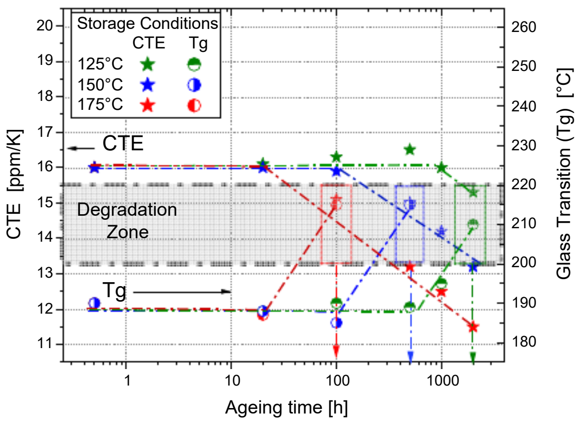


Fig. 2: Influence of storage conditions on thermomechanical properties (TMA).

b) Determination of time to degradation (t_{d_CTE} / t_{d_Tg}).

The time it takes to reach a significant change of glass transition (T_g) to values increased by +15 K (T_g) and of CTE to a lower value by -1 ppm/K are extracted from Figure 2 and listed in Table 5 as a function of storage temperature.

TABLE 5: TIME TO DEGRADATION EXTRACTED FROM TMA DATA.

	Exposed temperature		
	125°C	**150°C**	**175°C**
t_{d_CTE}	>1000h	>100h	>20h
t_{d_Tg}	>500h	>100h	>20h

c) Dynamical Mechanical Analysis (DMA) for determination of modulus and T_g

The results of the DMA in Figure 3 show the storage modulus (E') and the glass transition temperature (T_g). The maximum of the mechanical loss function (E'/E'') is defined as the T_g, which for the initial samples is at 215°C. It should be noted that each measurement method provides different characteristic T_g results, which is why it is essential to specify the measurement conditions and evaluation procedures in order to make meaningful comparisons. It can be observed that the temperature storage significantly effects the thermo-mechanical properties. At a storage temperature of 150°C there is a slightly increase of E' for a storage time up to 500h, whereas there is a significantly increase of T_g for exposure time up 100h. For the other storage conditions were observed a moderate changing of modulus but a significantly shift of T_g under 125°C and 175°C storage temperature. This behaviour is characterised by a further decrease of molecular chain mobility and an increasing dominance of glass fibre due to diminishing adhesion behaviour matrix and glass fibre, resulting in sligthly increasing stiffness

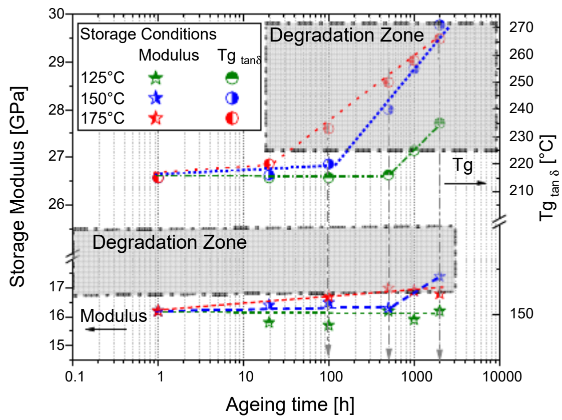


Fig. 3: Influence of storage conditions on thermo-mechanical properties (DMA) of core material.

Similar to the results from the TMA analysis, a shift in glass transition temperature towards higher values is also observed. Depending on the storage temperature, these changes in thermo-mechanical behaviour are achieved at different rates.

d) Determination of time for degradation ($t_{d\_E'}$ / t_{d_Tg})

The time it takes to reach a significant change of T_g to higher value of +15 K depending on storage temperature and for significant change of storage modulus (below T_g) to higher values (+/- 1 GPa) is referred as the time to degradation.

TABLE 6: TIME TO DEGRADATION EXTRACTED FROM DMA DATA.

	Exposed temperature		
	125°C	150°C	175°C
$t_{d\_E'}$	n.d.	>500h	>100h
t_{d_Tg}	>1000h	>100h	>20h

e) Warpage Analysis

The warpage measurements were performed on copper coated PCB samples which were stored in the same manner as described above. Warpage occurs due to the intrinsic stresses and the CTE mismatch of the different thin metal films and the substrate by variation of temperature. As thermo-oxidation effects lead to a lower CTE, the mismatch with the CTE of copper increases over ageing time. The initial warpage at room temperature is subtracted in order to visualize and compare the relative warpage changes occurring during temperature cycling.

In Figure 4, the relative warpage at the respective measurement temperatures for different ageing temperatures and times is shown. It can be observed that the samples stored at 125°C for 2000h show a relative warpage of approx. 250 µm. This value was defined as a maximum (uncritical) deflection. Measurement results at other storage temperatures indicate that max. deflection of 250 µm at higher storage temperatures already occurs after 100h at 175°C and 500h for 150°C.

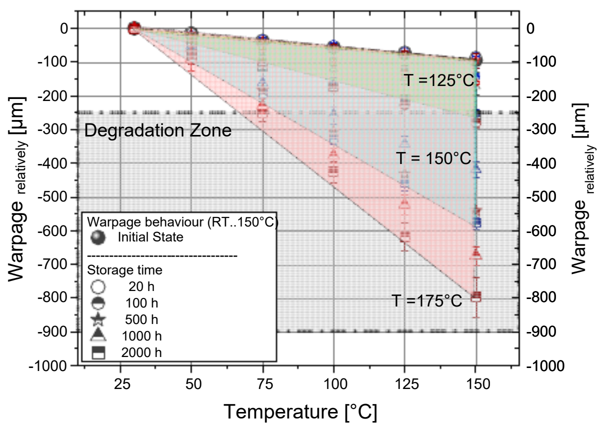


Fig. 4: Influence of storage conditions on warpage behaviour on copper-coated core material during temperature change between RT and 150°C for different storage temperatures (125°C, 150°C, 175°C) and times

f) Determination of time for degradation ($t_{d\_warpage}$).

The storage time it takes to reach a deflection of 250 µm depends on storage temperature and is referred to as the time to degradation $t_{d\_warpage}$.

TABLE 7: TIME TO DEGRADATION EXTRACTED FROM WARPAGE ANALYIS.

	Exposed temperature		
	125°C	150°C	175 °C
$t_{d\_warpage}$	>2000 h	>500 h	>100 h

Overall, it is evident that temperature storage significantly influences the mechanical property profile. A notable increase in modulus values and a significant shift or decrease in the mechanical loss factor are observed, but only after varying storage durations. This is attributed to a further decrease in molecular chain mobility and an increasing dominance of the glass fabric due to diminishing adhesion between the matrix and glass fabric, leading to higher stiffness. Similar to the results from the TMA analysis, a shift in glass transition temperatures towards higher values was also observed.

Depending on the storage temperatures, these changes in thermo-mechanical properties are achieved at different rates. It can be assumed that this ageing process is not yet complete.

D. High-frequency Parameters

a) Dielectric Analysis

The set of samples for the RF analysis provides a number of physical parameters which were evaluated and which allow for an in-depth discussion on the critical performance. First, the changes of ε_r and tanδ were measured without any metalized layer (pure dielectric analysis). Second, planar resonators were structed on metallised substrates. The ring and fork resonators provide information on the interaction of dielectric and metal layer when under accelerated ageing and the effective values of ε_r and tanδ were extracted.

RF Analysis of Pure Dielectric Analysis: The analysis of the pure dielectric is commonly performed with an external test fixture. In our case a split-cylinder resonator was employed. The detailed description of the characterization methods is out of the scope of the present paper and presented in [5-7]. The data from the pure dielectric characterisation is displayed in Figure 5. A significant increase of ε_r and tanδ with the different ageing time is observed. Furthermore, the higher the temperature, the higher the increase. The samples for 175°C and 1000h and 2000h however deviated from the trend. Further tests resulted in non-repeatable results for these two samples. A very high susceptibility to humidity was observed which was most likely caused by a proceeding decomposition of the material under test.

RF Analysis of Metallised Dielectric Analysis: The pure dielectric analysis provides the basis for the performance estimation of any interconnect or component. However, the layout of the individual structure and the metalized layer will impact the performance as well. In the present study, the effect resulting from the accelerated ageing is also changed depending on e.g. the percentage of the surface which is covered by the copper layer.

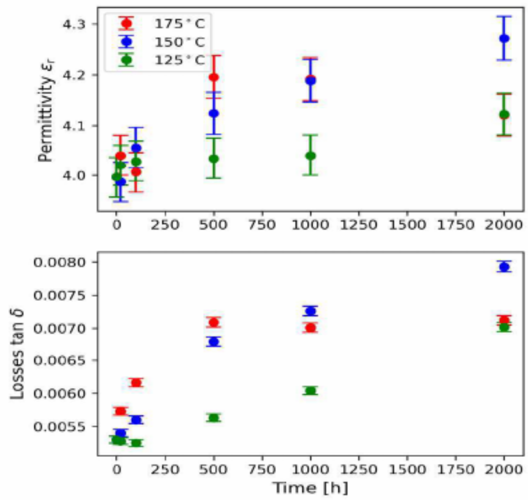


Fig. 5: Results of the characterization of the pure dielectric material by use of a split-cylinder resonator.

In order to quantify the impact of the accelerated ageing on actual RF components, two types of resonators were designed: a ring and a fork resonator. The underlying principle, the design and the evaluation of such resonators is detailed [5]. Figure 6 displays selected examples of the manufactured and aged structures.

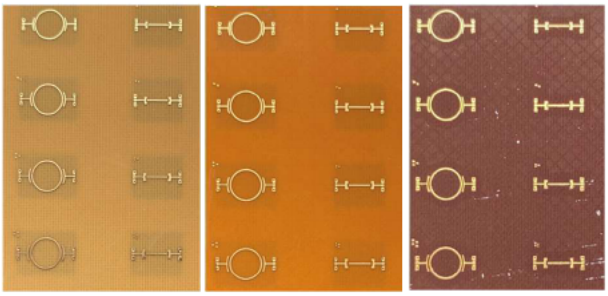


Fig. 6: Ring (left) and fork (right) resonators for the metalized dielectric analysis. Samples were stored at 175°C for 20h (left), 100h (centre) and 500h (right).

Based on the S-parameters of each resonator, the effective values for ε_r and tanδ were extracted. It is important to stress that the effective values include any changes to the materials due to the manufacturing process and any changes in the conductor performance, for example increased losses due to the surface finish or due to the oxidation of the copper during the ageing process.

Figure 7 displays the extracted effective dielectric properties from the ring and fork resonators. The initial losses are already higher when compared with the pure dielectric characterisation while the effective permittivity is initial lower; both for the reasons discussed above. Furthermore, the copper structures are more fragile than the non-metalized samples hence the increased variation within the dataset (e.g. effective tanδ extracted from a fork resonator after 20h at 125°C). Despite all these effects, the impact of ageing is still pronounced. We refrain from further detailed evaluation of the data due to the limited number of ageing temperatures.

b) Determination of time for degradation (t_{d_losses}).

Since the consequences of the changes in ε_r strongly depend on the design and functionality of any component which is build from the material, it is not possible to define a time for degradation based on the permittivity itself. However, the losses which are measured by tanδ can be evaluated in a general manner. We propose that an increase of the losses by 25% can most likely not be tolerated by any RF circuit. This criterion was used to extract the time to degradation (t_{d_losses}) for each storage temperature from the combined data of the pure and the metallised dielectric analysis. The values are listed in Table 8.

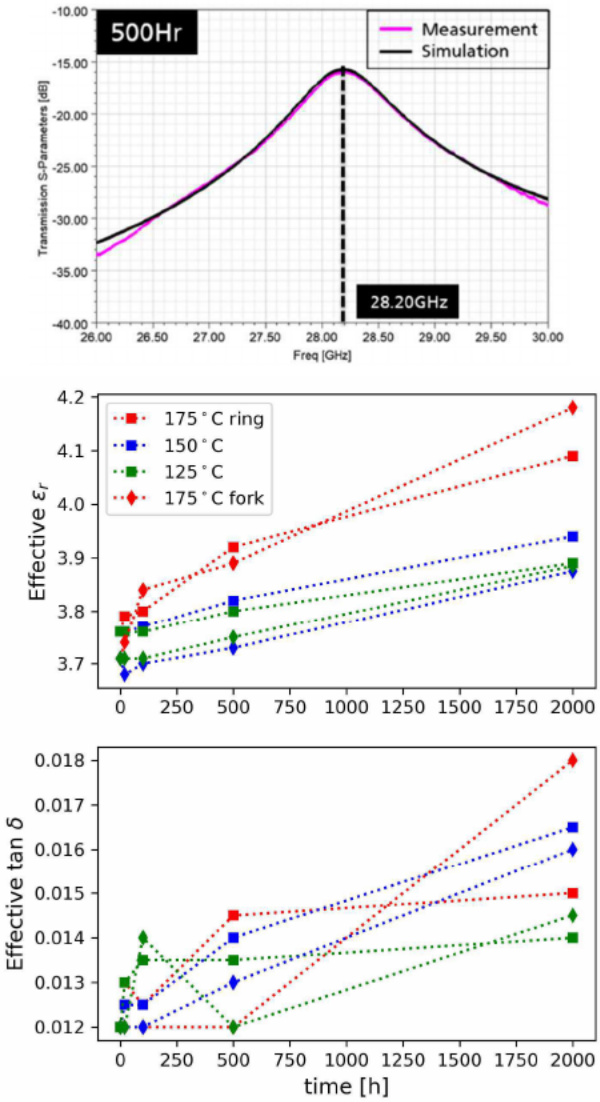


Fig. 7: Top: Example for the extraction of the effective ε_r and tanδ values from the S-parameter measurement via full wave simulation (fork resonator, 500h at 150°C),
In the two Graphs below: Results of the ring (squares) and fork (diamonds) resonator measurements. The lines are added to guide the eye.

TABLE 8: TIME FOR DEGRADATION EXTRACTED FROM DIELECTRIC CHARACTERISATION

	Exposed temperature		
	125°C	**150°C**	**175°C**
t_{d_losses}	>2000h	>500h	>100h

c) Antenna Analysis

The final step of the RF analysis is the measurement of antennas. To that end, single element patch antennas were designed, manufactured and aged together with the samples for the dielectric characterization. Figure 8 displays the initial state of the antenna together with the aged state for 2000h at 150°C. It is clearly visible how the main resonance is shifted to lower frequencies as a result of the accelerated ageing. Furthermore, the magnitude is significantly decreased which is most likely a consequence of the elevated losses in the dielectric substrate.

d) Determination of time to degradation ($t_{d\_antenna}$).

The extent to which the change in the dielectric properties influences a given interconnect or component depends strongly of the respective design. It is not possible to define a global threshold for the acceptable drift in dielectric properties. However, for components with specific applications, a threshold can be argued for. In the case of the current antennas for mmWave 5G communication systems, the antenna was designed for 29.5 GHz.

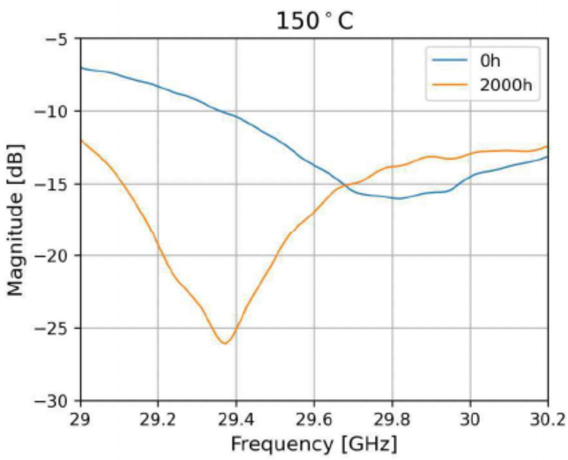


Fig. 8: S-Parameter of the single element patch antenna in the initial state and after 2000h at 150°C.

The threshold was set to the time when no proper resonance, and hence no usable radiation within the targeted frequency band was present in the S-parameters. The extracted $t_{d\_antenna}$ values are listed in Table 9.

TABLE 9: TIME FOR DEGRADATION EXTRACTED FROM ANTENNA MEASUREMENTS.

	Exposed temperature		
	125°C	150°C	175 °C
$t_{d\_antenna}$	>2000h	>500h	>100h

III. DISCUSSION

The storage of samples under different temperatures leads to a significant change of color depending on the storage temperature and duration. This color change is caused by thermo-oxidative degradation processes in the polymer matrix. Selected thermo-mechanical and dielectrical parameters were used to evaluate the ageing process, which provided evidence of ageing-related material changes. In combination, these ageing-related changes in material properties of the studied substrate material, also lead to a significant change in the warpage behaviour of the metal coated laminates. In particular, the increased temperature-dependent warpage behaviour correlates with the change in CTE to lower values and glass transition temperature to higher values.

Table 10 lists the extracted threshold values (t_d) for selected mechanical and dielectrical properties of different ageing temperatures. For all material properties, a significant change could be observed over the duration of the accelerated ageing process.

In Figure 9, the results from Table 10 are summarized. It can be observed that significant changes in mechanical and dielectric properties occur in relation to the storage temperatures, similar to the time to degradation of color changes, a property much easier to characterize. The graph shows further that the temperature loading conditions play an important role in the chemical reaction behaviour of the investigated laminate.

TABLE 10: TIME TO DEGRADATION OF RELEVANT PARAMETERS FOR DIFFERENT TEMPERATURES.

	Exposed temperature		
	125°C	150°C	175°C
t_{d_color} (color change)	>1000h	>100h	>20h
$t_{d\_E'}$ (modulus (E'))	n.d.	>500h	>100h
t_{d_Tg} (T_g DMA)	>1000h	>100h	>20h
t_{d_CTE} (CTE)	>1000h	>100h	>20h
t_{d_Tg} (T_g TMA)	>500h	>100h	>20h
$t_{d\_warpage}$ (warpage)	>2000h	>500h	>100h
t_{d_losses} (dielectric losses)	>2000h	>500h	>100h
$t_{d\_antenna}$ (antenna shift)	>2000h	>500h	>100h

Storage at high temperatures accelerated the chemical ageing process. In contrast, the chemical processes slowed down for lower temperatures. This reaction kinetic can be described by the Arrhenius approach. By applying Equation 1, the activation energy ΔH was calculated for diffferent elevated temperatue and time intervals on the example on Tg degradation and color change.

ΔH = 13,983 kJ/mol → 1,2 eV (Tg_DMA/Color change)

The activation energy, represented by ΔH, is the minimum energy required for a chemical reaction to occur. It is the energy barrier that must be overcome for a significant degradation of the material.

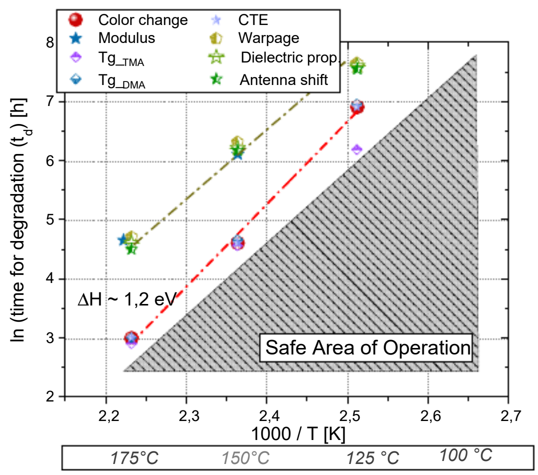


Fig. 9: Arrhenius plot of time to degradation (t_d) vs. inverse temperature.

Below the determined critical times and durations, a zone is defined, where no degradation can be observed and which can be referred to as Safe Area of Operation. Based on extrapolation of the Arrhenius equation, there will be no significant degradation effects expected in this zone which may impact the material properties of the used laminates. By application of the calculated activations energies, it is furthermore possible to predict the lifetime of the PCB material with accelerated lifetime tests. Thus reliability can be assured for lower temperatures than the test temperatures and much longer lifetimes than testable in the lab.

IV. Conclusions

In this study the thermo-oxidative ageing processes of a laminate material was investigated. Thermo-oxidative ageing processes were observed under defined laboratory conditions. Significant changes in mechanical and dielectric properties were observed, with simultaneous changes of sample color. Using of Arrhenius approach, it become possible to calculate activation energy ΔH for selected mechanical and dielectric parameters. For this purpose, times to degradation were determined depending on storage conditions (temperature, time) for the significant changes of properties and color. Outside of the so-called degradations zone a Safe Area of Operation (SAoO) were defined, where no measurable degradation effects may impact the material behaviour. By means of both, SAoO- concept and activation energy, critical times to degradation can be derived for other, e.g. lower temperatures. With these data, estimates can be made for long-term stable assemblies, devices using experimentally validated data from laboratory and applied to field applications.

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