

# Effects of Polymer Material Variations on High Frequency Dielectric Properties

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## ABSTRACT

In high frequency signal packaging, the plastic dielectric material takes on an increasingly important role in the performance of the signal transmission. Variations within the plastic can occur as a result of a number of manufacturing and environmental processes. These variations can be sufficient to change the dielectric properties. The extent of change to the dielectric properties of polymer materials as a result of controlled variations to major filler additives, moisture and temperature has been investigated. The combined effects of moisture and temperature can cause changes to the dielectric constant of certain materials by more than 30 %.

## INTRODUCTION

Traditionally, the electrical performance assessment of plastic materials used in electronic packaging focused simply on their insulative nature (high dielectric strength) and their ability to physically isolate adjacent metal conductors. As the frequency of the electrical signals in circuits increases and the spacing between conductors decreases, the electromagnetic properties in the plastic materials play an increasing role in the propagation of the electrical signal.

Two important electromagnetic properties in plastic materials are the relative permittivity (or dielectric constant) and dissipation factor (or dielectric loss tangent). The appropriate dielectric constant of a polymer along with the correct geometric design of the system helps reduce the signal-propagation delay and distortion through the electronic package, and minimize cross-talk. Materials with a low dielectric loss tangent can reduce attenuation in circuits, and can improve signal integrity.

When designing high speed, high frequency connectors, it is critical to couple the dielectric properties of the plastic housing material with the geometric design in order to obtain the appropriate electrical performance over the desired frequency range. The potential flaw in this design approach is the assumption that the dielectric properties of a specific plastic resin grade will remain constant. A specific grade of plastic resin can undergo a number of changes that can cause shifts in the dielectric constant ( $Dk$ ) and loss tangent ( $\tan \delta$ ) of the material. These dielectric properties of plastic materials are directly influenced by the chemical make-up of the resin formulation (that can include the base polymer, reinforcing fillers, flame retardants), and to a lesser extent processing modifiers, colorants, plasticizers, lubricants, etc. Lot-to-lot variations in the concentrations of the major resin additives (glass fillers and flame retardants) can cause changes in the dielectric properties of a particular resin grade.

The dielectric properties of plastic resins are also influenced by the orientation, density and mobility of the dipole moments of polymer repeat units. Even resins from within a specific lot of material can be processed in ways that can lead to variations in polymer and reinforcing fiber orientation, degree of crystallinity, and density. Such variations can cause changes in the  $Dk$  and  $\tan \delta$  as a result of different molding parameters. Even after a product has been manufactured, there are environmental factors that can impart changes in a resin that can affect the dielectric properties. Increases in temperature can increase the mobility of polymer chains, especially

thermal excursions through a plastic's glass transition temperature. As the largest contribution to the polarizability of polymers, the orientational polarizability results from a change in alignment of the permanent dipole moments in the polymer to that of an applied electric field by the physical movement of the group associated with the dipole [1]. Thus the increased mobility of the polymer chains at elevated temperatures can lead to changes to  $D_k$  and  $\tan \delta$ .

Moisture absorption in a resin can have a combination of effects on the dielectric properties. Moisture can act as an additional component in the material that can have an additive effect on the dielectric properties. With the  $D_k$  of water being  $\sim 50$  at a frequency of 10 GHz [2], a relatively small absorption of moisture into a resin can cause a significant change. In materials such as polyamides that have an affinity for moisture, water can induce plasticization in the resin. This can cause a shift in the glass transition temperature of the material to lower temperatures, increasing the mobility of the polymer chains even at room temperature. Again, a change in the mobility of the polymer chains can cause a change in the dielectric properties.

There is evidence in the literature that at least some of the factors mentioned above can significantly change the  $D_k$  of materials [3] [4] [5]. To what extent these variations affect the dielectric properties of thermoplastic materials is not well characterized, especially at high frequencies ( $> 1$  GHz). If the dielectric properties of the plastic material change, the electrical performance of a connector may suffer. This paper seeks to characterize the changes to  $D_k$  and  $\tan \delta$  associated with variations in materials caused by moisture absorption, reinforcing filler quantity, flame retardant content, and temperature.

## EXPERIMENTAL

Evaluations of the effects of glass filler and flame retardant content on the dielectric properties used polyamide 4-6 type material supplied by DSM Engineering Plastics. The grades studied were Stanyl<sup>®</sup> TE300 (unfilled), Stanyl<sup>®</sup> TE200 F6 (with a 30 wt.% glass fiber content), and Stanyl<sup>®</sup> TE250 F6 (with 30 wt.% glass fiber and an undisclosed flame retardant). Using these three resin grades allowed for the isolation of the material variations related to the major additives. And in some cases, mixtures of these grades provided intermediate levels of the additives. The materials used to study the effects of moisture and temperature were two polyamides (Stanyl<sup>®</sup> TE200 F6 from DSM Engineering Plastics and Zytel<sup>®</sup> HTN FR52G30 from DuPont<sup>®</sup>), three polyesters (Valox<sup>®</sup> 420 SE0 from SABIC Innovative Plastics, and Thermx<sup>®</sup> CG933 PCT & Zenite<sup>®</sup> 6130L from DuPont<sup>®</sup>), a syndiotactic polystyrene (Questa<sup>®</sup> EA535 from Dow Chemical), and 3112 RTV silicone from Dow Corning<sup>®</sup>.

Two techniques were used for measuring the dielectric properties of the plastic materials. A stripline method was used when studying the effects of moisture [6]. Using this technique,  $D_k$  and  $\tan \delta$  data was obtained over a frequency range between 0.1 to 20 GHz. Samples analyzed using the stripline technique consisted of a length of copper conductor sandwiched between strips of the plastic, and were constructed by a custom process. This method provided a single monolithic structure with the center conductor strip tightly surrounded by the dielectric material. Samples approximately 12 mm wide and 2 mm thick of various lengths were utilized for the testing.

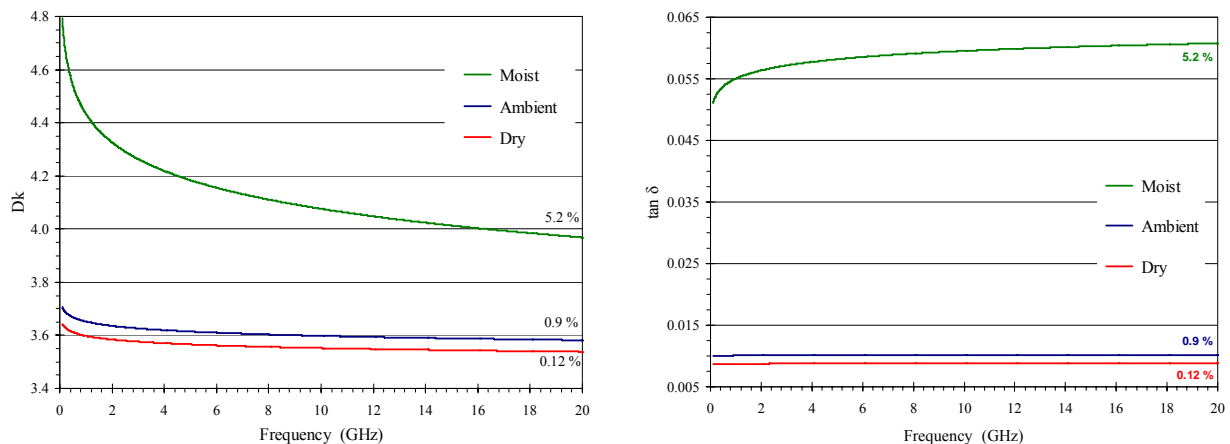
A second method for measuring  $D_k$  and  $\tan \delta$  in this study was through a split-cylinder resonant cavity technique. In this technique, a thin sample is placed in the gap between the two shorted cylindrical waveguide sections. Resonant measurement methods provide an accurate means of obtaining  $D_k$  and  $\tan \delta$ , but they typically provide data at only one frequency.

However, unlike the stripline method, the split cavity resonator is more easily adapted for higher temperature measurements. Disks measuring 30 mm in diameter and approximately 1 mm thick were used when analyzing the dielectric properties using the resonant cavity technique. These samples were injection molded using consistent molding parameters.

In varying the moisture content, ovens were used to accelerate either the drying or moisturization of the samples. A set of five samples of each material were dried in a forced air convection oven for 3 days at 90 °C. A separate set of five samples were moisturized to the point of saturation using a humidity chamber set at 85 °C/85 % R.H. for a duration of 7 days. The dried and moisturized samples were stored in moisture barrier bags between testing. Moisture content in the dry samples was measured by a Computrac® VaporPro® moisture analyzer from Arizona Instruments. The moisture content in the ambient and moisturized samples was determined by gravimetric methods relative to the dry mass of each sample.

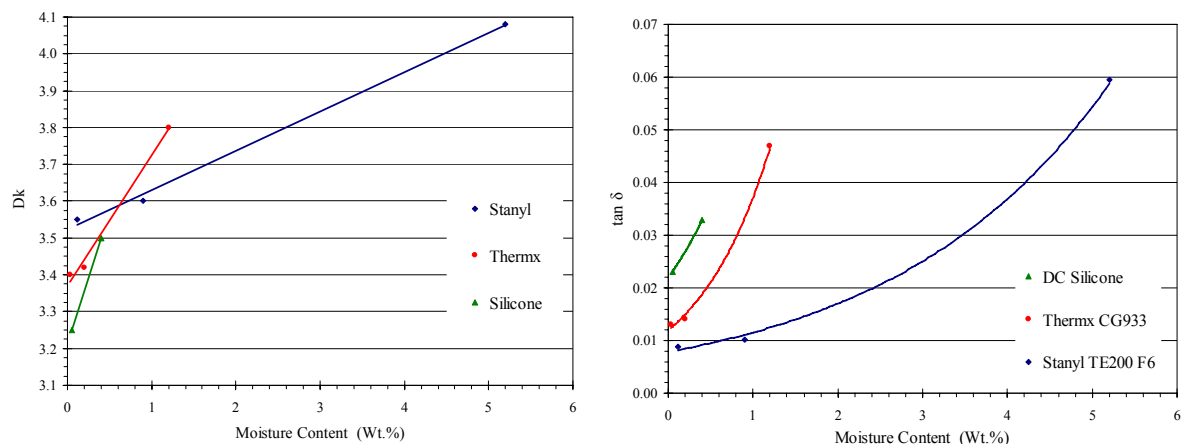
## RESULTS AND DISCUSSION

The stripline method was used to measure the effect of moisture absorbed into a plastic resin. Moisture was found to have a significant effect on the dielectric properties of the polymers in this study. The Stanyl® polyamide, Thermx® and RTV silicone each showed an increase in their dielectric constants and  $\tan \delta$  across a broad spectrum of frequencies. An example of this behavior is shown in the plots of Dk and  $\tan \delta$  vs. frequency for the Stanyl® resin that was tested when dry, at ambient storage conditions and when moisturized (Figure 1). The ambient measurement was not made on the silicone material. While the magnitude of the effect of the added moisture on Dk decreases with increasing frequency, it remains significant in the 10 to 20 GHz range.



**Figure 1.** Shifts in the broadband Dk and  $\tan \delta$  for the Stanyl® polyamide material (moisture contents listed as wt.%).

The rate of the change in the dielectric properties with increasing moisture content at 10 GHz for the Stanyl®, Thermx® and silicone using the stripline method is shown in Figure 2. The increase in the dielectric constant with increasing moisture content fits a linear relationship reasonably well for each of the resin types. At 10 GHz, the Dk of the Stanyl®, Thermx® and silicone increased by 15 %, 12 % and 8 %, respectively. Much larger increases were observed for the effects of moisture on  $\tan \delta$  (575 %, 260 % and 40 %, respectively). The change in Dk and  $\tan \delta$  was found to be fully reversible. When the moisturized Stanyl® sample was re-dried to



**Figure 2.** Effect of moisture on the Dk and  $\tan \delta$  for Stanyl<sup>®</sup>, Thermx<sup>®</sup>, and silicone resins at 10 GHz.

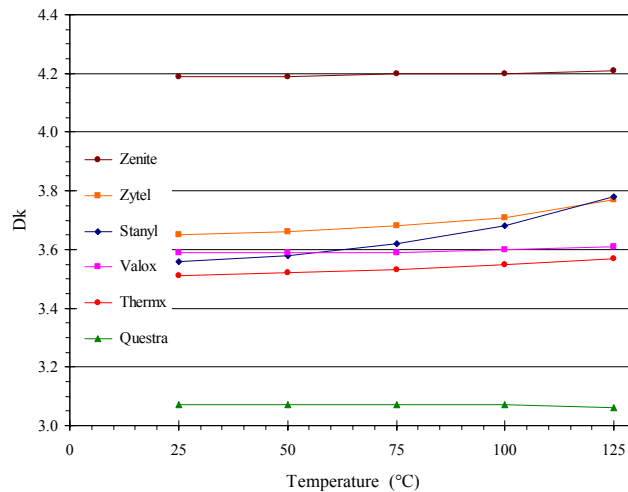
remove moisture, the Dk and  $\tan \delta$  returned to their pre-moisturized levels.

The impact that the moisture has on the dielectric properties varies for the different polymer materials, especially the Stanyl<sup>®</sup> polyamide. This may be due in part to the interaction water has with polyamides compared to the other materials. The impact of moisture on the Thermx<sup>®</sup> and RTV silicone materials is consistent with what would be expected of free (unbound) liquid water, if the effect of the moisture was strictly additive (based on a Dk of 100 % water equal to 50). The Stanyl<sup>®</sup> polyamide material deviates from this correlation with a lower rate of Dk increase with increasing moisture content. This is likely due to the fact that some fraction of the water molecules absorbed into the polyamide are bound to the polymer through Hydrogen-bonding. The dielectric constant of tightly bound water molecules has values similar to the dielectric constant of ice, which is only 3.16 [7]. It is believed that the decreased slope in the relationship of Dk with moisture content in the Stanyl<sup>®</sup> polyamide from Figure 2 is due to Hydrogen-bonded water molecules that reduce the effective dielectric constant of water present in the resin system. The Thermx<sup>®</sup> and silicone materials lack such interactions with water, and so the moisture in these systems is free to exhibit dielectric properties closer to that of liquid water.

The interaction of moisture in a polymer resin may also affect the dielectric properties as a result of plasticizing the material. This is again the case for polyamide resins such as the Stanyl<sup>®</sup> resin. The temperature dependency of the Dk is mainly due to the temperature dependence of the relaxation time of the materials [8]. Since the relaxation time of dielectric materials can affect their dielectric properties, changes to the mobility of the polymer chains can cause changes in the Dk and  $\tan \delta$ .

The consequence of this is that the impact of moisture that was observed for the Stanyl<sup>®</sup> polyamide in Figure 2 may be a combination of effects from 1) the additive contribution of the water molecules, and 2) the increased mobility of the polymer chains as a result of water's plasticizing effect. In order to attempt to separate out the effects that moisture has on the dielectric properties of polymer systems, the Dk of a number of polymer resins were measured at elevated temperatures both in the dry and moisturized states. Using a split-cylinder resonator that was fitted with a heated jacket, the Dk of the materials were measured at temperatures between 25 and 125 °C and at a fixed frequency of 16 to 17 GHz (depending on the polymer being measured).

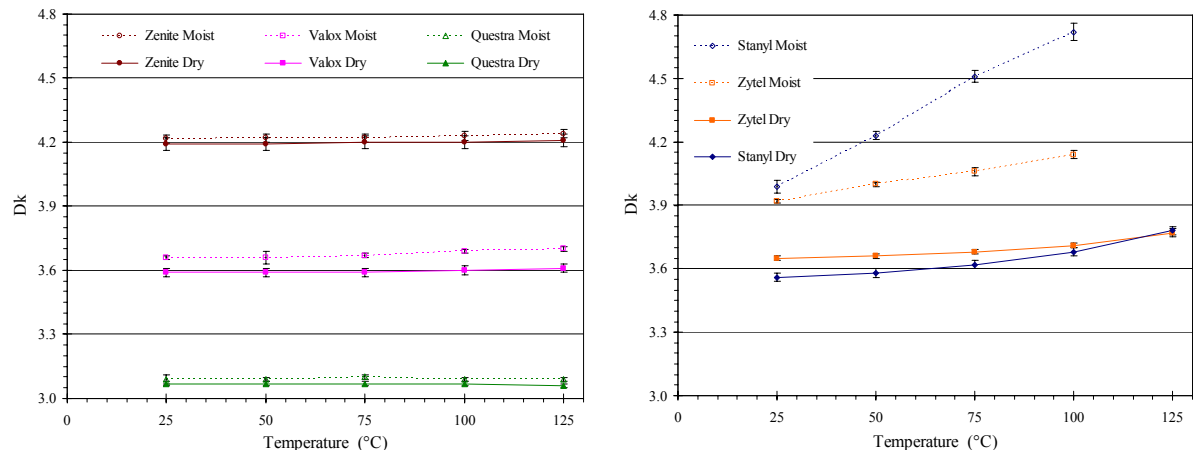
The changes to the Dk of the various materials with respect to temperature are plotted in Figure 3. While there is a small increase in the Dk with increasing temperature for the Zytel<sup>®</sup> and Stanyl<sup>®</sup> polyamide materials, the Dk of the other materials remain largely unaffected by even a 100 °C increase in temperature. This, despite the fact that each of the materials exhibits a glass transition temperature ( $T_g$ ) from a glassy to a rubber, more mobile state within the temperature range tested. It may have been expected that the Dk of the materials would have seen a greater increase when the test temperatures exceeded their glass transition temperatures. The reason for lack of increase in Dk may lie in the fact that, as in mechanical testing, that apparent  $T_g$  of a material is dependent on the frequency at which the material is tested.



**Figure 3.** Effect of temperature on the Dk of various dry materials at ~ 16.5 GHz.

Figure 4 shows the effects of the Dk of dry and moisturized materials at various temperatures. With the exception of the polyamide materials, the Dk of the moisturized materials were unaffected by temperature. There was a small shift in the Dk due to the additive effect of moisture, but like the dry material, the Dk did not increase with temperature. In the case of the polyamide resins (Zytel<sup>®</sup> and Stanyl<sup>®</sup>), there was a significant increase in the impact that moisture has on Dk at higher temperatures. Whereas the increase in Dk for the Zytel<sup>®</sup> and Stanyl<sup>®</sup> polyamides due to moisture absorption was 7 % and 12 %, respectively at 25 °C, the increase in Dk was much larger (12 % and 28 %, respectively) when measured at 125 °C. The polyamide materials showed a steady, linear increase in their response rates of Dk with temperature. Since the change in Dk at the various temperatures is a direct result of the increased moisture in the materials, it is believed that the increasing impact that temperature has on Dk at elevated temperatures is a function of the dielectric behavior of water.

The effects that major filler materials have on the dielectric properties of a polymer resin were also studied using the resonant cavity method. Specifically, the change in the Dk and  $\tan \delta$  as a function of glass fiber and flame retardant contents were measured on the Stanyl<sup>®</sup> resin at ambient conditions. The Dk exhibited a moderate increase with increasing glass fiber content, from 3.27 (unfilled) to 3.67 (30 wt. % glass fibers). The  $\tan \delta$  remained relatively unchanged compared to the effects of moisture and temperature, decreasing from 0.0151 to 0.0133. Taking into account that the lot to lot variation of reinforcing glass fiber should not vary by more than  $\pm 2$  or 3 wt.%, the effect that variations in glass fiber content might have on the Dk and  $\tan \delta$  of glass fiber reinforced resins is less than 1 %.



**Figure 4.** The effects of temperature on the Dk of dry and moisturized samples of Zenite<sup>®</sup>, Valox<sup>®</sup>, and Questra<sup>®</sup> (a); and of Stanyl<sup>®</sup> and Zytel<sup>®</sup> (b).

As with the glass fiber content, the flame retardant exhibits a moderate increase in dielectric constant (from 3.62 to 3.93), but only a minor change in  $\tan \delta$  (from 0.0133 to 0.0141) compared to the effects of moisture and temperature. Even a nominal variation in relative flame retardant content of 5 weight percent due to lot to lot variations would not be expected to cause a change in the dielectric properties of a flame retarded resin by more than 0.5 %.

## CONCLUSIONS

While typical variations in major additives (such as reinforcing glass fibers and flame retardants) in polymer resins have little effect on the dielectric properties of the materials, variations due to environmental factors such as moisture and temperature can have significant effects. The impact of moisture on Dk and  $\tan \delta$  is significant for all polymer materials tested. This impact of the moisture is diminished in materials that absorb and interact with moisture such as polyamides, but the reduced effect is offset by the relatively large amount of moisture that they can absorb. Polymers that don't associate with moisture may show a greater effect on the increase in Dk, but this is mitigated by the small amount of moisture that may be absorbed into these materials.

The dielectric properties of polymers like polyesters and polystyrene, that do not significantly absorb moisture, are surprisingly stable over a broad temperature range up to 125 °C. It is believed that the delay in the materials' response to the high frequency measurements shifts the apparent glass transition temperatures to higher values, and prevents a more significant increase in the dielectric properties when the materials are tested above their accepted  $T_g$  values. When moisture is present in the system, an increase in temperature can lead to a dramatic increase in the dielectric properties. In materials that absorb a significant amount of moisture, the combined effects of moisture and increased temperature may have a synergistic action that causes a greater increase in the Dk than the material would experience with either moisture or temperature as separate factors.

## REFERENCES

1. F. Mercer and T. Goodman, *High Perform. Polym.*, **3**(4), pp. 297-310 (1991).
2. E. Nyfors and P Vainikainen, *Industrial Microwave Sensors*. Norwood, MA, Artech House, 1989, pp. 41-49.
3. J.-M. Heinola and J.-P. Ström, *Elect. Insul. Mag.*, **23**(3), p. 23-29, (2007).
4. C. Zou, J. Fothergill and S. Rowe, *IEEE Transact. Dielect. Elect. Insul.*, **15**(1), pp.106-117, (2008).
5. S. Singha and M. J. Thomas, *IEEE Transact. Dielect. Elect. Insul.*, **15**(1), pp. 12-23 (2008).
6. C. Morgan, *DesignCon08*, 5-TA4, Santa Clara, CA. 2008.
7. V. F. Petrenko and R. W. Whitworth, *Physics of Ice*, Oxford, Oxford University Press, 2005, p. 95.
8. K. C. Kao, *Dielectric Phenomena in Solids*, London, Elsevier Academic Press, 2004, pp. 97-99.

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