Understanding Phase Versus Temperature Behavior

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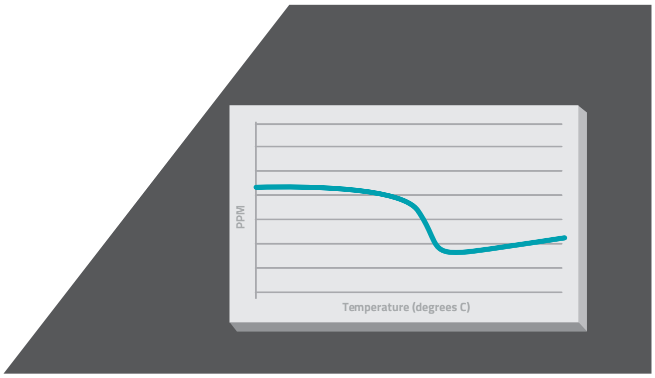
INTERCONNECT TECHNOLOGIES

"THE TEFLON™ KNEE"



Introduction

Understanding complex microwave transmission concepts can be difficult. Understanding complex material properties can also be difficult. Understanding phenomena that combine both of these can be mind boggling. Phase stability versus temperature is one of these phenomena.

This application note will provide the reader with a basic grasp of the situation. Before we can discuss phase stability we need a basic understanding of phase length and phase delay. Phase length, also known as electrical length, is the number of wavelengths in the cable assembly at a given frequency.

All cable assemblies have a mechanical length and an electrical length. The electrical length is usually specified in degrees. Phase delay is the time that it takes a signal to travel from one end of the cable to the other relative to the time it would take in an equivalent air line. This is also sometimes referred to as the signal delay or propagation delay, and is usually measured in nano-seconds.

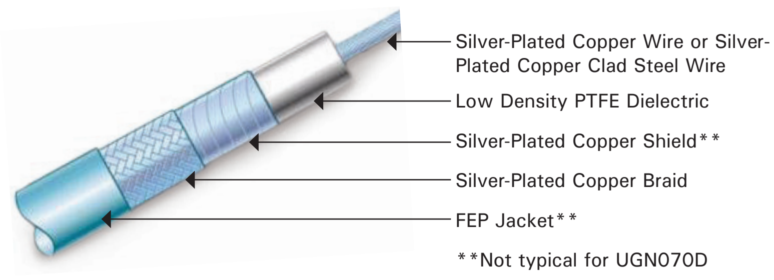
A microwave signal propagates in a coaxial cable at a speed that is primarily dependent on the dielectric constant of the insulating material between the center conductor and the outer conductor. Dielectric constant relates the ability of a material to store charge, relative to air. A material with a high dielectric constant can store a lot of charge. The function of a cable assembly, however, is to conduct the charge, not store it. Storing charge is the equivalent of slowing down the signal. Thus, microwave cable assemblies use insulating materials with a low dielectric constant, such as Teflon™, to minimize signal delay.

Given the discussion so far, one might conclude that any calculation of "phase" in a cable assembly would contain components of physical length, signal frequency, and dielectric constant or velocity of propagation. Indeed this would be a correct conclusion and a cursory examination of the equations for calculating phase behavior would show that all of them contain some form of each of these components. However, individual materials and their interactions also have a significant impact.

Living in a Material World

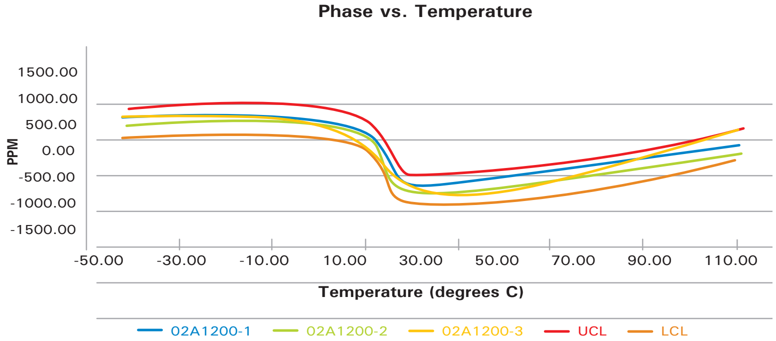
A typical microwave coaxial cable is a composite structure consisting of metal conductors separated by a polymer dielectric. The entire assembly is then encapsulated with a polymer jacket as shown in Figure I. The behavior of these various materials with temperature, and their interactions with one another will govern the overall phase versus temperature response of the assembly.

Figure I. Typical microwave cable construction



Phase change versus temperature curves can vary significantly from one type of cable to another and from one manufacturer to another. This is often a source of confusion since the basic construction is very similar for most microwave cables. Figure II shows a typical phase change versus temperature curve for a high performance cable assembly. This application note will focus on the large change that occurs between 19 and 25 ° C.

Figure II. Phase Change versus Temperature for UFB311A



The Teflon™ Knee

Since, we have already concluded that phase length will be influenced by physical length and dielectric constant, changes in either or both of these variables with temperature will have an impact on the overall phase versus temperature response. Consider first the physical changes that occur within the dielectric as a result of temperature changes.

Typically microwave cable assemblies use poly-tetrafluoro-ethylene (PTFE, a.k.a. Teflon™) or expanded PTFE (e-PTFE) as the dielectric layer. PTFE undergoes dimensional changes with temperature that can be measured via a thermo-mechanical analysis

(TMA). A typical TMA curve for unconstrained, solid PTFE is shown in Figure III. The most distinct feature of this curve is that at approximately 19°C there is a dramatic change in the dimensions due to a change in the crystal structure. Structural phase changes occur in crystals as the atoms rearrange themselves into structures that are more energetically favorable. This abrupt change in physical dimensions manifests itself in the phase versus temperature curve of PTFE microwave cable assemblies in what is commonly referred to as the "Teflon™ knee"

The basic building block of PTFE is two carbon atoms (ethylene) with each carbon atom bonded to two fluorine atoms (tetrafluoro). These basic units are then strung together (poly) to form the polymer material. The fluorine atoms are relatively large and are strongly bonded to the carbon atom. Because of this they do not like to be too close to each other or stacked directly on top of one another. This is known as steric repulsion.

At low temperatures, PTFE forms a 13/6 helix structure to minimize stacking energy yet still accommodate steric repulsion. The 13/6 designation denotes that 13 CF2 groups are required to form 6 twists of the helix. Each CF2 group has a 13.8° angular rotation with respect to the one next to it. Thus, 13 CF2 groups form a repeating unit that encompasses a 180° rotation of the helix.

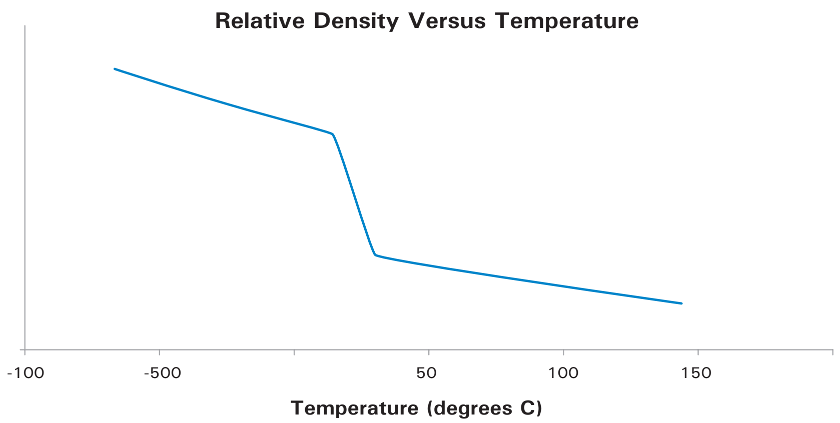
This terminology is used to describe the smallest repeating unit that can fully reflect the polymer structure, but a molecule of PTFE is actually much longer than 13 CF2 groups. The helical structure results in long straight rod-like molecules that fold at regular intervals to form a banded "crystal" structure. To further increase stacking efficiency, these bands then stack up next to one another fairly tightly in what is referred to as a triclinic lattice, similar to a box-spring only more tightly packed.

The triclinic lattice represents the tightest possible packing density for the PTFE helices, almost an intertwining of the helices. As the temperature increases above 19° C, the vibrational energy of the system increases and the fluorine atoms must move further apart to accommodate the repulsive forces between them. To accomplish this the helix begins to untwist to a 15/7 conformation. In other words, now 15 CF2 groups and 7 twists are required to complete a 180° rotation of the helix. As the helix untwists it becomes longer, analogous to the uncoiling of a spring. Furthermore, the now untwisting helices cannot be stacked as tightly together and the whole crystal structure changes to a hexagonal phase.

The hexagonal crystal has a lower packing density than the triclinic crystal, allowing the fluorine atoms to move farther apart. As a result there is a dramatic 1.3 to 1.8% volume expansion of the PTFE material, causing dramatic electrical changes. The Knee is Backwards, isn't it? If PTFE expands dramatically at the knee, and it does, then shouldn't the electrical length be getting longer instead of shorter? This is where an understanding of both physical and electrical properties is important.

Consider for a moment, what is happening to the density of the dielectric. Figure IV depicts the relative density versus temperature of an unconstrained PTFE material. The density is at a maximum at the coldest temperature. As temperature increases, thermal expansion causes the density to decrease almost linearly. At the knee, or transition zone, the structure expands rapidly and subsequently there is a discontinuity in the density versus temperature curve. Above the transition zone, the density is again decreasing linearly as a result of thermal expansion.

Figure III. Typical Cable Attenuation

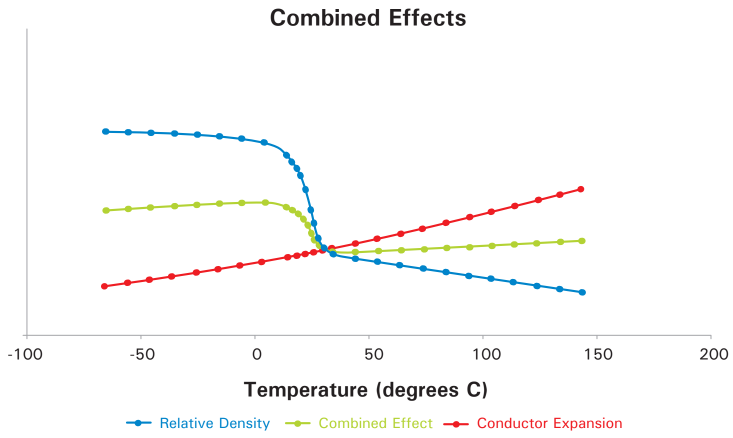


As the apparent density decreases the effective dielectric constant decreases. Lowering the dielectric constant increases the velocity of propagation, thus reducing the electrical length. Thinking in terms of phase delay, the electrical signal can travel faster through air than it can through the dielectric. Reducing the density adds more "open space" to the dielectric, thus increasing the propagation speed and decreasing the phase delay. So, the knee in the phase versus temperature curve shows a sharp decrease in the phase length as a result of the sharp decrease in the effective dielectric constant.

Conductor Behavior

Compared to the thermal behavior of the PTFE dielectric, the conductors are much less complex. The conductors expand with increasing temperature in a linear and predictable manner consistent with their coefficient of thermal expansion. As the center conductor expands it increases in physical length and consequently electrical length. In Figure V the linear expansion curve of the center conductor is overlaid on the density curve of the dielectric showing the individual effect on phase of each of these components. By adding the two effects together, the net result is the typical phase versus temperature curve shown originally in Figure II.

Figure III. Typical Cable Attenuation



Conclusion

Phase versus temperature behavior is a complex phenomenon that reflects both physical and electrical changes in coaxial cable assemblies. Outside of the transition zone known as the "Teflon™ knee", phase versus temperature behavior is governed primarily by thermal expansion effects. Inside the transition zone a structural phase change occurs in the PTFE dielectric material that accounts for the sudden discontinuity in the curve. This phase change causes a relatively large expansion in the dielectric layer causing a decrease in the apparent density and a subsequent decrease in the effective dielectric constant. The velocity of propagation increases in this region resulting in a decrease in the phase or electrical length.

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