Recent Developments in Coaxial Interconnection Cable Materials to Minimize Temperature Induced Phase Errors

David Slack, Times Microwave Systems, Wallingford, CT, david.slack@timesmicro.com

Abstract— PTFE (Dupont's Teflon®) has been the transmission line dielectric of choice for several decades.

PTFE undergoes a material phase change at room temperature. It undergoes a virtual "step function" volumetric change and a change in relative permittivity as well as presenting a "hysteresis" effect on electrical length changes.

These variables in electrical length can be difficult to reliably predict and account for via system software or other means and may contribute to systematic performance degradation.

Developments in both organic and inorganic dielectric materials,have yielded dramatic improvement in several of these basic performance metrics.

This article will compare and contrast several coaxial cable technologies:

- Electrical length change as a function of temperature
- Electrical length tracking of multiple cables as a function of changing temperature
- Electrical length tracking of multiple cables when they transit through diverging thermal zones
- Electrical length repeatability vs. multiple iterations of temperature cycling.

Additive phase noise as a function of mechanical vibration and the interactions between the conductor structures and the dielectric materials, as they pertain to the electrical length parameters will also be discussed.

I. Introduction

Oliver Heaviside noticed that wrapping a telegraph wire in an insulator improved both the signal quality and effective distance of the communications signals. In 1880 he patented the world's first coaxial cable. In 1929 engineer's at AT&T's Bell Telephone Labs patented the first modern coaxial cable. Crude by today's standards it was constructed of two concentric metal tubes separated mostly by air.

In the 1930's gutta percha (a natural form of rubber) was the primary dielectric of choice for early flexible coaxial cables. Polyethylene became the predominant insulator of choice during the World War II years. In the 1950's "foaming" processes were developed that reduced cable capacitance and loss characteristics.

In the 1960's solid, full density polytetrofluoroethylene (PTFE), or "Teflon®" gained widespread use. Its higher temperature ratings, lower loss tangent, lower dielectric constant and uniform properties over a wide range of temperatures and frequencies caused it to be almost uniformly desirable as a coaxial cable dielectric.

In the 1970's and 1980's manufacturers began using expanded, low density versions of PTFE to further improve its desirable properties.

In the 1990's the increasing demand for electrical length stability caused manufacturers to begin using ultra low density PTFE dielectrics. These products were a definite improvement but still had some inherent limitations.

Chief among these limitations is the phase vs. temperature "knee": a step function change in electrical length caused by the base material properties of the PTFE molecules. This effect could be minimized but is physically impossible to eliminate.

In 2004 coaxial cable products using TF4® technology was introduced to specifically address this problem. In 2015 further refinements and process developments have culminated in an improved TF4® technology with some very clear advantages over PTFE dielectric material in phase sensitive applications.

II. Performance Metrics

The ideal microwave cable assembly would have zero loss, zero reflected energy and zero electrical length. These ideal properties would be maintained across all environmental conditions that the system components would ever see.

In our practical world we endeavor to achieve as much of the ideal as possible.

This is certainly true with regards to electrical length changes of coaxial cable assemblies as its surrounding environment changes temperature.

A. Phase Change as a Function of Temperature

It is common knowledge that the metals used to construct coaxial cable assemblies have positive temperature coefficients of expansion. Almost as commonly known is that electrical length and physical length are directly related. It would seem obvious that with an increase in temperature, an increase in physical length would occur and thus an increase in electrical length would follow.

In fact the reverse is true; most microwave cable assemblies exhibit a negative temperature coefficient of electrical length. Fig. 1 illustrates the temperature effect on electrical length for an idealized cable assembly.

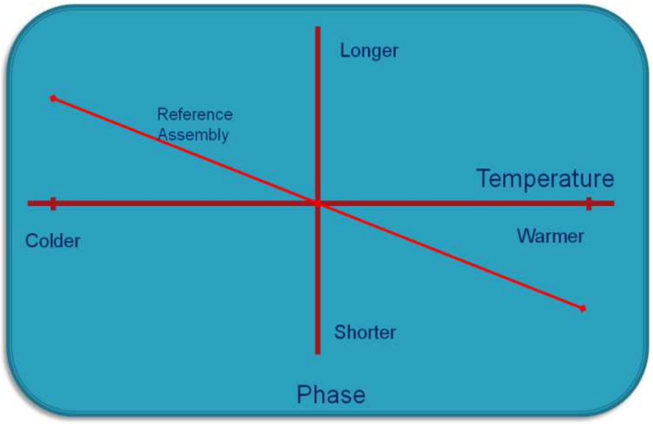

Figure 1: Temperature Effect on Electrical Length

The axial length of the center conductor increases directly with temperature. The outer conductors increase in length directly with temperature as well, which has the effect of changing the diameter of the outer conductor in a direct relationship to temperature change.

This results in a small density change in the dielectric core which changes the net relative permittivity. The end result of these interactions is that the changes in relative permittivity have an effect on electrical length that is opposite that of the expansion-contraction of the metals.

This is a critical point as this phenomenon makes it theoretically possible to balance the two effects and achieve zero phase change with respect to temperature.

A practical cable assembly, using PTFE as a propagation medium, will always have a step function change in dielectric constant at room temperature with a corresponding change in electrical length. Fig. 2 illustrates the temperature effect on the phase on a practical, PTFE based coaxial cable.

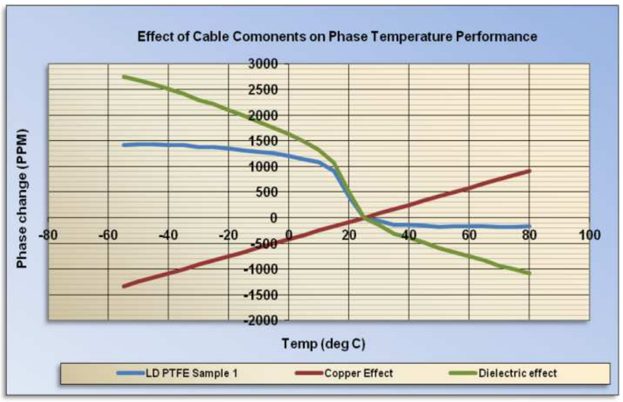

Figure 2: Temperature Effect on PTFE Based Coaxial Cable

- Copper has a POSITIVE temperature coefficient of expansion of 17 PPM/deg C
- For this construction the dielectric has a NEGATIVE effect on electrical length of 23 PPM/deg C
- The dielectric also exhibits the PTFE phase transition “knee”

B. Phase Tracking as a Function of Temperature

As a practical matter phase matched cable assemblies do not retain the relative phase match as temperatures are varied. The degree to which they maintain their initial relative match is referred to as phase tracking. Fig. 3 illustrates how two cable assemblies, initially phase matched at room temperature, might track as a temperature changes.

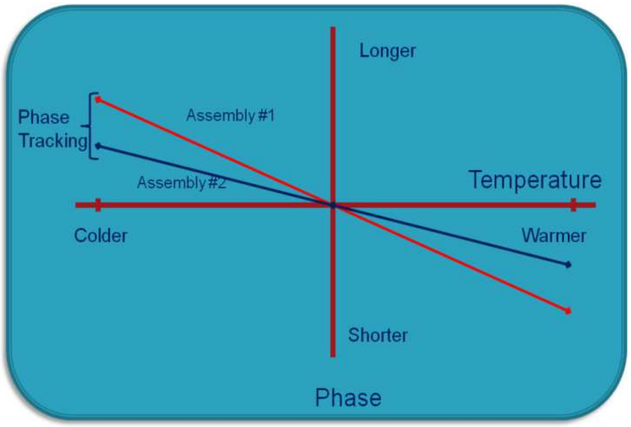

Figure 3: Phase Tracking vs. Temperature

Several factors contribute to excellent phase tracking performance. Most critical is uniformity per unit length of cable. Capacitance uniformity, impedance uniformity and mechanical uniformity of the conductors are all crucial to tracking. The worst case phase matching, at all temperatures, is a function of the initial match plus the phase tracking characteristics. Fig. 4 illustrates how phase tracking over temperature is also a function of the degree to which cables are matched at room temperature.

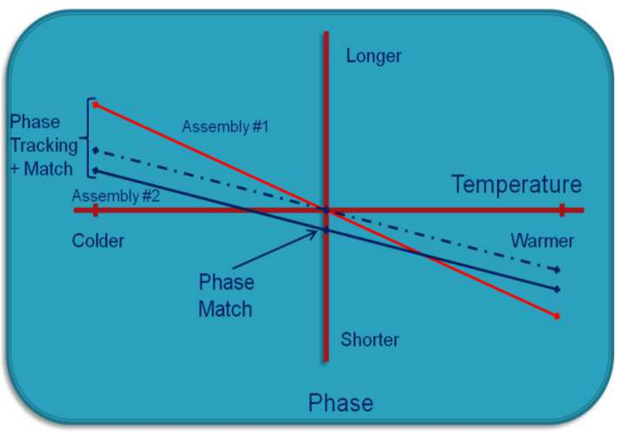

Figure 4: Phase Tracking plus Initial Phase Match

C. Phase Matching at Room Ambient Temperature

Cable assemblies that are intended for use in phase sensitive applications are phase matched to each other. As environmental temperature changes occur the ensuing phase change will be proportional to the initial electrical length.

Assemblies having the same electrical length, and subjected to the same temperatures, should maintain their phase matched characteristic.

In addition to the electrical and mechanical consistency the degree to which a grouping of cable assemblies is initially matched factor into phase tracking performance.

D. Phase Repeatability as a Function of Temperature

Similar to phase tracking is phase repeatability. Virtually all system applications will go through multiple dozens or hundreds of temperature cycles. It is important to know that each iteration of a specific temperature yields a consistent and repeatable electrical length. Semi-rigid cable tends to be the most consistent in this regard. A well made flexible cable can also be quite repeatable but they have inherent variability due to the interaction between and expanding-contracting dielectric core and the outer shield construction.

In fact, practical phase tracking vs. temperature is the composite of all of these effects. Fig. 5 is an illustration of how these effects combine to affect practical phase tracking of groups of phase matched cable assemblies.

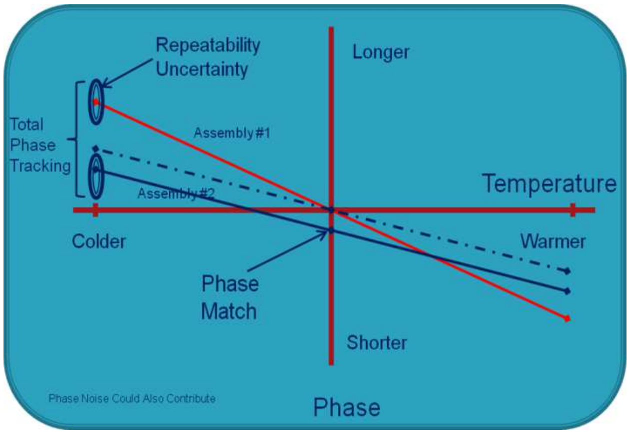

Figure 5: Combined Effects and Phase Tracking vs. Temperature

E. Phase Hysterisis as a Function of Temperature

Fig. 6 shows that the PTFE material further complicates the phase temperature characteristics of cable due its hysteresis properties.

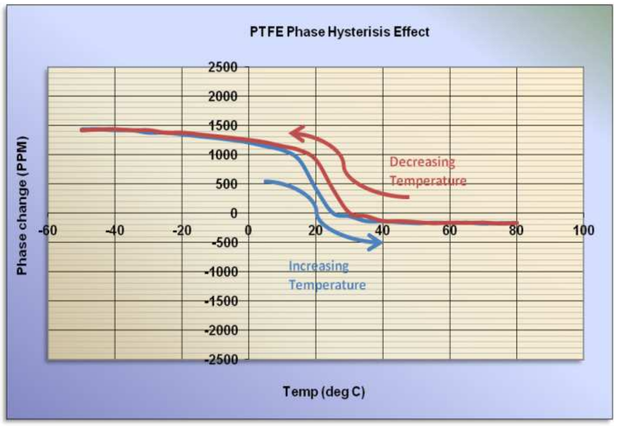

Figure 6: Hysterisis Effect of PTFE Dielectric

PTFE has an array of characteristics that make it highly prized as a cable dielectric material. One of the critical drawbacks is the fact that the PTFE material undergoes a molecular phase change between 18 and 20 degree Celsius.

This phase change causes a 1.5% volumetric change with a corresponding change in dielectric constant. This phase change causes a relatively abrupt change in electrical length.

This effect can be reduced by using less dense PTFE dielectric constructions but it cannot be eliminated.

In addition the phase change begins at different temperatures as temperature increases than when temperature is decreasing. This hysteresis has a significant degradation on phase tracking performance.

III. PERFORMANCE OF TYPICAL MICROWAVE CABLE

PTFE dielectrics are, by far, the most commonly used for the construction of microwave and millimeter wave cable assemblies. They are used in two basic categories, full density (ε_r = 2.01) and low density (ε_r = 1.73).

There are also ultra low density PTFE (ε_r = 1.42) cables which have optimized the extent to which a phase stable cable can be constructed using PTFE. These cables tend to be extremely prone to mechanical damage as the ultra low density construction offers very little by way of mechanical support.

In general the plastic density per unit length of expanded PTFE dielectrics has consistency variations that translate directly to phase tracking degradation. This is most prominent at the temperature extremes of the cables rated operating temperature. Fig. 7 overlays the phase vs. temperature "footprints" of several high performance coaxial cable products.

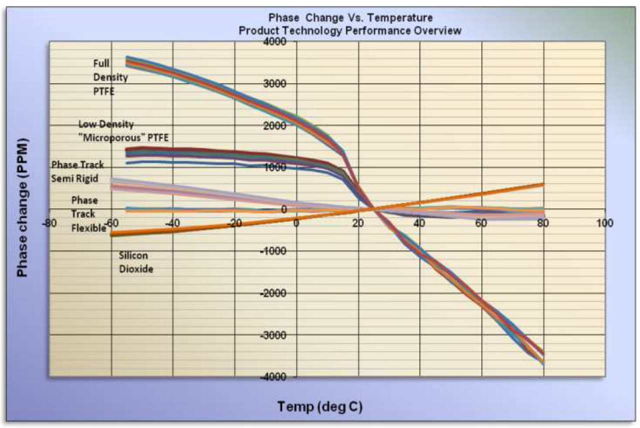

Figure 7: Phase vs. Temperature "Signature" of Various Coaxial Constructions

A. *Full Density PTFE Dielectric*

Solid core, full density PTFE cables have a very mechanically robust dielectric core. The phase temperature slope is the highest of the variants and the effects of the molecular phase transition is pronounced.

B. *Low Density "Microporous"PTFE Dielectric*

Low density PTFE dielectric cores are made in several ways all using variations of a similar process. Full density PTFE material is placed under tension and stretched under controlled conditions and at elevated temperatures.

The material is cooled while under tension and the result is an "expanded" PTFE material that can be used to construct cable dielectric core.

These products probably comprise the bulk of cable used in phase sensitive microwave applications. The low density material minimizes the phase temperature slope as well as the "step-function" change in electrical length at the phase change transition temperatures.

IV. ALTERNATIVES TO PTFE

Several alternatives to PTFE based coaxial cables have been developed and have exhibited significant improvement in system level performance. All of these have eliminated the phase temperature "knee" allowing for improved balance of the conductor – dielectric effects on phase vs. temperature performance. Figs. 8 and 9 illustrate the contrast in shape and tracking performance between PTFE and TF4™ products.

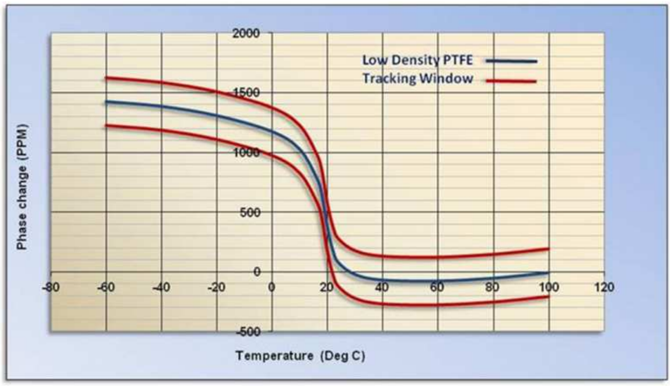

Figure 8: Typical Phase vs. Temperature PTFE Coaxial Products

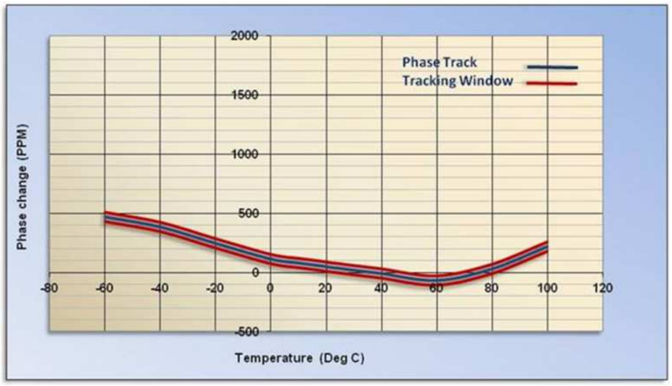

Figure 9: Typical Phase vs. Temperature TF4™ Coaxial Products

A. Silicon Dioxide Semi-rigid Cable Assemblies

Silicon dioxide is a material that has been used as a cable dielectric for a number of years. The silicon dioxide material is extremely hygroscopic. As such it must be used in cable assemblies that are fully hermetically sealed (leak rate less than 5 x 10^{-8} Atm-cc/sec He).

These cable assemblies are semi rigid in construction using a copper clad stainless steel jacket and welded to a stainless steel connector body.

Given the consistent geometries of the cable and the inorganic nature of the dielectric, these cables display the ultimate in phase vs. temperature repeatability and tracking performance.

In addition the materials employed in the manufacture of these products produce an extremely robust cable assembly. The dielectric has the properties of compacted sand providing excellent support for the outer conductor when under mechanical duress.

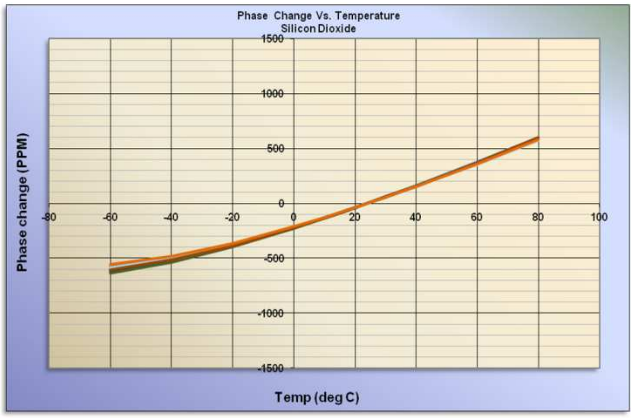

Figure 10: Phase vs. Temperature Silicon Dioxide Coaxial Products

The stainless steel and the silicon dioxide materials are both extremely radiation and corrosion resistant. They are suitable for use from absolute zero to well over 600^{o} Celsius. They have an impressive pedigree in aerospace and spaceflight applications.

B. TF4™ Semi-rigid Cable Assemblies

A more recent development is TF4™ fluoropolymer blend developed at Times Microwave Systems. This material has similar temperature ratings as PTFE but does not have the abrupt shift in dielectric constant. Because it can be melt extruded it is much more consistent per unit length than expanded PTFE thus presenting greatly improved phase tracking and repeatability performance. The semi rigid construction provides the same uniform tube structure as the silicon dioxide. This construction provides repeatability performance that rivals the silicon dioxide without necessitating stainless steel conductors and specialized connectors. These cables can be manufactured with commercial off-the-shelf connectors, such that might be put on any PTFE based semi rigid cable.

Another advantage of this material is the "closed cell" nature of the dielectric core. To achieve the balance between conductor effects and dielectric effects the dielectric core is required to be less dense than what is required to be mechanically robust. An ultra low density (V_p = 84%) TF4™ dielectric has the same durometer measurement as a standard density (V_p = 76%) expanded PTFE tape. This allows for a mechanically robust cable without the necessity of heavy and expensive mechanical strength members. Fig. 10 and fig 11 offers a comparison between the SiO2 dielectric and semi rigid coaxial cable assemblies manufactured with the TF4 material.

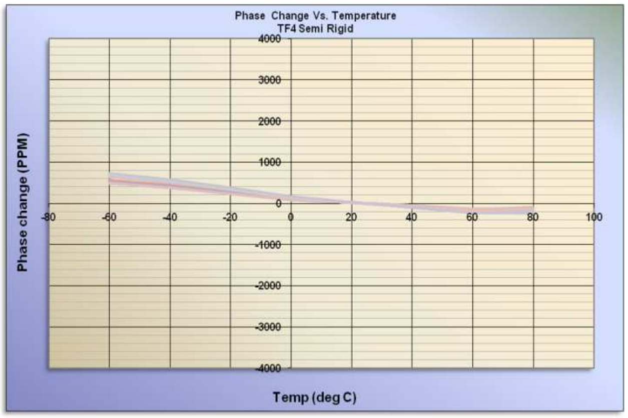

Figure 11: Phase vs. Temperature TF4™ Semi Rigid Coaxial Prdoducts

C. TF4® Flexible Cable Assemblies

Just as the TF4™ dielectric provides a drop-in replacement for PTFE in semi rigid constructions it also provides similar benefits to flexible cables.

These cables are sized similarly to PTFE cables. In addition they look and handle almost identically.

The benefit comes from significant improvement in phase change with temperature, phase tracking with temperature and phase repeatability with temperature.

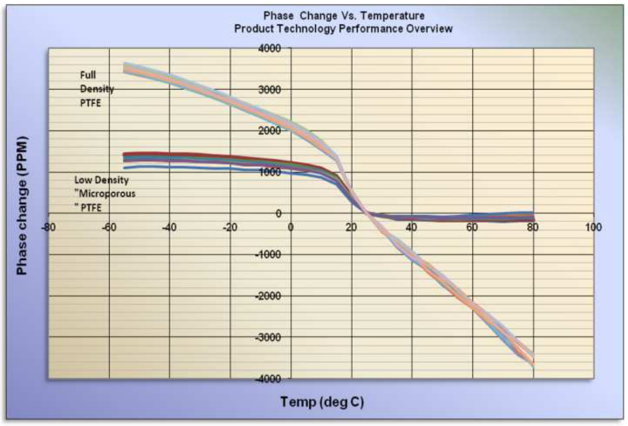

Figure 12: Phase vs. Temperature Comparison Full Density and Low Density PTFE products

V. PHASE PERFORMANCE COMPARISONS

A. Phase Change vs. Temperature

Figs. 12 and 13 compares the phase temperature characteristics of flexible PTFE and TF4™ products. Each cable type includes 10 identical phase matched assemblies to offer a sense of the phase temperature characteristic but the tracking characteristics as well.

This overlay of the five cable technologies provides dramatic contrast of the relative phase vs. temperature “footprint” of each product type.

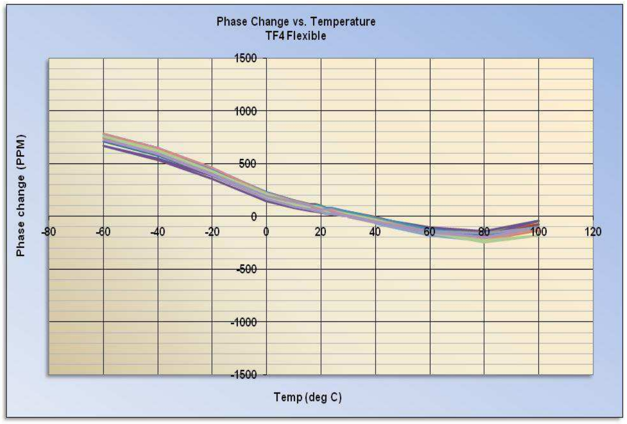

Figure 13: Phase vs. Temperature "Signature" of TF4™ Flexible Coaxial Products.

It is plainly evident that cable made using a dielectric core of solid PTFE has a very steep phase temperature slope that becomes extreme at just around room temperature. The phase temperature slope between +15 C and +25 C is about -130 PPM/deg C. This rate of electrical length change is over four times faster than the cold temperatures below +15 C. Below room temperature the electrical length temperature coefficient is -30 PPM/deg C.

A similar change in the phase temperature slope characteristic occurs with all PTFE based cable dielectrics. The magnitude of the slope change can be minimized by reducing the dielectric core density, but it can never be eliminated as it is a fundamental property of the PTFE material.

The reasonably optimized "microporous" PTFE product illustrated in FIG 12 demonstrates this effect. The effect of the plastic have been fairly well balanced against the effect of the expansion-contraction of the metals in the temperature ranges above and below the PTFE material phase transition temperatures.

The phase vs. temperature slopes are relatively flat outside of the room temperature range. It still demonstrates a reduced, but significant phase vs. temperature slope within the +15 to +25 degree C range of temperatures. The phase temperature slope in this zone is still about -85 PPM/deg C.

It should be pointed out that several manufacturers offer products with an "ultra" low density PTFE dielectric core. These products have achieved propagation velocities in excess of 85% with a further reduction in the phase temperature slope in the room temperature region.

These products tend to over compensate the dielectric-conductor balance with a slight positive phase temperature slope above and below the PTFE "knee" and a further reduction in the electrical length slope within the material phase transition temperature band.

The characteristics of these products have not been illustrated in this article as the dielectric core, become so mechanically fragile that they are impractical for all but the most benign applications. When the dielectric offers such little mechanical support it often gives way to mechanical degradation and associated structural return loss and stability problems.

Both the silicon dioxide and the TF4™ dielectric technologies solve both problems without adding size or weight.

The PhaseTrack® products and the silicon dioxide product have been reasonably well optimized as far as the conductor-dielectric balance without any hint of a slope change at any temperature within the operating range. It achieves this with mechanical durability and handling properties equivalent to, or better than the low density microporous PTFE product.

B. Phase Tracking vs. Temperature

Another property that is quite significant with regards to coaxial interconnect products is the ability of multiple signal paths to maintain their relative electrical length relationships across the entire system operating temperature range. This degree to which cable assemblies "track" each other is especially critical in parts of the hardware architecture that cannot be calibrated out or accounted for via other means.

As a general rule the critical property of a coaxial cable assembly with regards to phase tracking is consistency per unit length of cable.

This consistency means dielectric density per unit length of cable, conductor consistency per unit length, material properties, conductor geometries, manufacturing process conditions etc.

Referring again to FIG 7 one can identify some reasonably clear empirical trends. Each of the five technology examples is illustrated using 10 identical cable assemblies which have been phase matched at room ambient temperature.

By inspection one notices that solid dielectrics track better than less dense dielectrics and semi-rigid assemblies track better than flexible constructions (another example of the impractical nature of the ultra low density PTFE technologies).

FIG 12 and FIG 13 illustrate the improved tracking performance of the TF4™ material over the micro porous PTFE. Both of the products that produced the data in these two figures were manufactured using identical constructions with the exception of the dielectric material. Both of the constructions were a standard flexible cable design. A group of PTFE cables tend to track to within ± 200 PPM around a nominal phase temperature profile. An identically constructed TF4 cable product would track to within ± 100 PPM.

When the wire weave “basket” construction of the outer conductor used in a flexible cable is replaced with a solid tube, the tracking performance is further improved to ± 50 PPM. The silicon dioxide product, with its solid geometries, inorganic dielectric material and fully welded construction provides the ultimate in tracking performance at ± 25 PPM**.**

C. Phase Repeatability vs. Temperature

A similar but subtly different attribute of phase temperature performance is the concept of phase “repeatability”. This is the measure of how well a cable returns to a given electrical length over the course of multiple iterations away from, and back to a given temperature.

This attribute is closely associated with phase tracking. In fact, without good repeatability than good tracking performance would be only a statistical anomaly and a very unlikely event.

FIG 14 illustrates the phase repeatability performance of an ultra low density PTFE product and compares it to the identical construction using a TF4™ dielectric.

The chart plots the electrical length performance of the two assemblies, at -60 C and at + 100 C. The red “constellation” of symbols is the PTFE product and the green the TF4 product.

At both temperatures the variance of the TF4 is about one quarter of the variance of the PTFE product. This is one of the attributes that provides the improved phase tracking vs. temperature of a bundle, or network of cable assemblies.

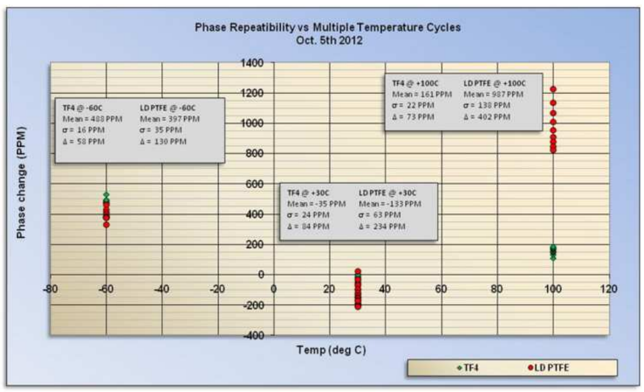

Figure 14: Phase Repeatability vs. Temperature Comparison of TF4™ and PTFE Coaxial Products

D. Phase Tracking vs. Diverging Thermal Zones

The discussion thus far has been under the assumption that all parts, of all the cable assemblies being discussed were held at the exact same temperature. As a practical matter this is almost never exactly true. Quite often cables will have slightly different routings through sections of the hardware that are slightly different in temperature.

As an example of how this might affect system performance refer again to FIG 7. The solid, full density PTFE cables track quite a bit better than their low density cousins.

As long as the cables are exactly matched in temperature they will maintain this tracking. Once they transit even slightly different temperature zones the tracking degrades quickly. The larger the magnitude of the phase vs. temperature slope the more the phase tracking will degrade.

FIG 15 quantifies the case of two full density PTFE cables at the extreme of a ± 2^{o} C temperature environment. The graph illustrates the phase vs. temperature response of two cable assemblies that are 4^{o} C apart from each other.

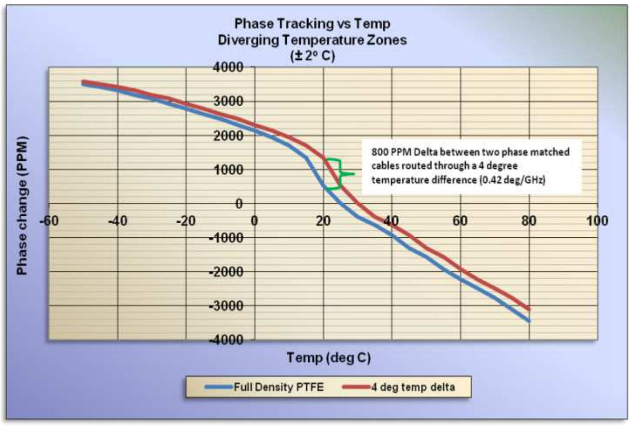

Figure 15: Phase Tracking Under Mildly Diverging Temperature Zones

Assuming the overall system undergoes the full environmental temperature range, and the thermal consistency of the system hardware causes a 4^{o} C differential between the two cables, then there could easily exist an 800 PPM difference of electrical length of the two cable assemblies. For a lower density PTFE cable this value is reduced to approximately 500 PPM.

Of course this maximum difference occurs at the environmental temperature where the phase temperature slope is steepest. It stands to reason that the flatter the phase temperature slope the less sensitive system performance will be to slight “hot spots” within the system environment.

FIG 16 provides a comparison of all the cable technologies discussed with regards to phase tracking with a 4^{o} C temperature differential between the routing of two identical assemblies.

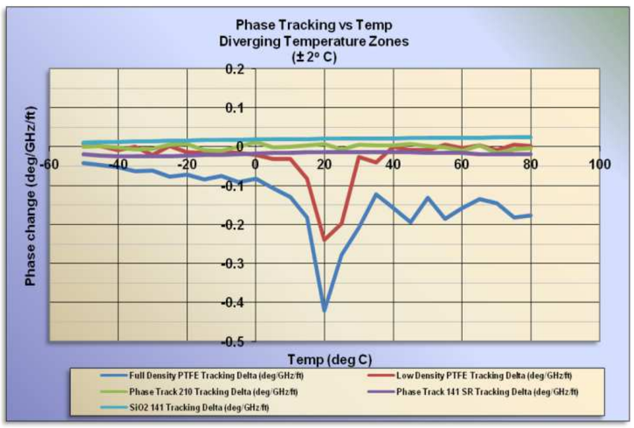

Figure 16: Product Comparison of Tracking Under Divergent Temperature Zones

E. Product “Blending”

There may be circumstances where only the absolute minimum of phase change vs. temperature can be tolerated and absolute phase tracking is essential.

In these special cases technology “blending” techniques have been used with excellent results.

The TF4™ dielectric technology has a very slight negative slope to its phase vs. temperature characteristic.

The silicon dioxide technology has a very slight positive slope to its phase vs. temperature characteristic.

When two cable assemblies; one using TF4™ semi rigid and the other using silicon dioxide semi rigid, are connected in series the net result is that of offsetting the phase temperature slopes of the two technologies.

The effect of each of the two assemblies is proportional to their overall length of the combined pair. By adjusting the electrical length of the two assemblies, the phase temperature slope can balance out and effectively cancelled.

In Fig. 17 the negative phase temperature slope of the TF4™ semi rigid is combined with the positive phase temperature slope of the silicon dioxide. The result is a virtually flat phase vs. temperature response from -40 to +60 Celsius.

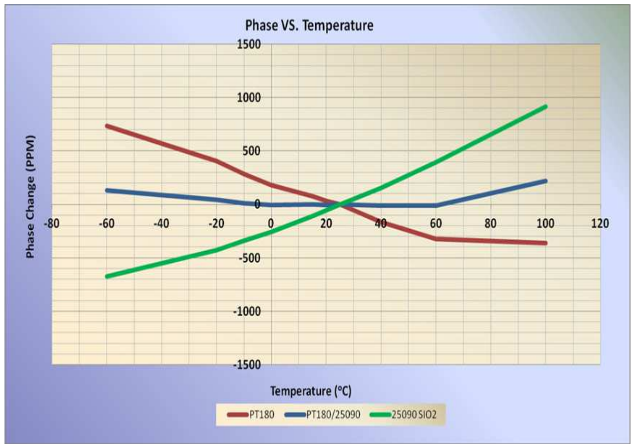

Figure 17: Example of Product Technology "Blending"

VI. CONCLUSION

Excellent phase temperature performance is certainly desirable in phased array antennas and other system architectures. It is also important in achieving and maintaining optimum test equipment calibration.

This is especially true in lab environments which typically are maintained at the worst temperature range for PTFE performance. Going from a cool room temperature to a warm room temperature can have a profound effect on phase sensitive measurements.

Regardless of the application, when dealing with phase sensitive equipment it is important to consider the effects that even basic components may have on overall performance.

While no existing technology can currently offer the ideal “transparent” interconnect, there is certainly a wider variety of options than may be commonly understood.