1

Facts about PTFE coaxial cables
Part 1

Dipl. Ing. (FH) Stefan Burger | DeltaGamma Consult

The author Stefan Burger

graduated in 1986, receiving his Engineer (FH) Diploma (similar to a Masters degree) from the University of Applied Science in Offenburg. He remained at the university as a research associate until 1990 when he started working in the R&D Department at Endress + Hauser in Maulburg. Here he was involved in RADAR-based level measurement devices until 2001, his particular responsibilities being the development of antennas and pressure-resistant RF-connectors, among other things.

From 2001 to 2011 he designed filters and duplexers for base stations at Panasonic Electronic Devices in Lüneburg, being entrusted with life-time and power-durability simulations.

In 2012 he founded his own enterprise, Delta Gamma Consultant (www.delta-gamma.com), in Hampton, Australia. Since 2014 he has been working as an exclusive consultant in the area of high-frequency and instrumentation for elspec GmbH in Geretsried, Germany.

1.1

Interesting facts about PTFE coaxial cables

Dipl. Ing. (FH) Stefan Burger | DeltaGamma RF-Expert

Content

Coaxial cable with dielektrikum made from PTFE

Preface

Coaxial cables with low losses and a broad temperature range usually use PTFE (Polytetrafluoroethylene) as the isolating material. At elspec we also use PTFE: for the last 32 years it has been the most frequently-ordered basic material besides copper, silver and steel. It is indispensable as requirements have become in-creasingly high, and precise, stable measurements are a necessity.

Therefore, it is of particular concern for the RF-specialist elspec to give an overview of the latest re-search about, and applications of PTFE. We wish to share insights about the properties and the limita-tions of this material, and summarize the various publications on the topic.

The combination of a silver-plated copper wire with a mantle made of PTFE is a highly interesting mix. Both materials are very different. PTFE is the insulator in RF-technology and has, in addition to many advantages, also a few special basic characteristics which the user should definitely be aware of: e.g. the PTFE-knee or the pre-aging required to achieve phase-stability in measurement cables.

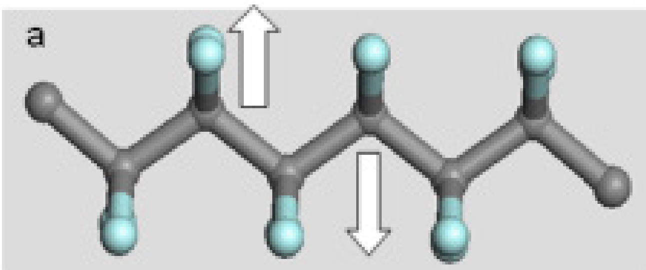
Polytetrafluoroethylene (PTFE) is a synthetic with very good chemical stability and a broad temperature range. In the high-frequency range this polymer has only small losses and is therefore very popular.

PTFE was discovered in 1938 by the chemist Roy Plunkett while he was working on coolants for refrig-erators. At first, there was no technical use because the material is complex and expensive to manufac-ture. It is, however, resistant to almost all aggressive media and only becomes unstable in the presence of strong reducing agents such as elemental fluorine at higher temperatures. Its first technical use was in the context of uranium enrichment, safeguarding containers against corrosive uranium hexafluoride. The DuPont company marketed PTFE under the brand name Teflon [1]

PTFE has a very small friction coefficient and remains flexible down to cryogenic temperatures (-269°C). It can, on the other hand, also be used up to temperatures of above 250°C and melts at about 330°C. [2, 3]

The high viscosity of PTFE in the melted state is a disadvantage since it is almost impossible to use the material for injection moulding or blow moulding. Shaping processes only work with extrusion or sintering.

In PTFE, every carbon atom is connected in both directions to another carbon atom. The remaining two orbitals are occupied by fluorine. The fluorine atoms are located almost symmetrically to the polymer fibre so that the dipole moments compensate each other. As a consequence, the properties are only slightly depen-



dent on frequency. In comparison, water has a pronounced dipole moment and is heavily dependent on frequency. This is utilised when e.g. heating food.

.

At temperatures below 19°C the fluorine atoms are not exactly opposite each

other as shown in the above figure but are slightly offset. Along the polymer fibre, 26 carbon atoms form one 360°-rotation over a length of 1.68 nm. This distance increases to 1.95 nm at 30°C, translating into a large difference in length and a reduction of permittivity.

Under atmospheric pressure, the crystal structure changes in relation to the temperature. At low tem-peratures it has a well-oriented hexagonal structure with a 360° rotation, At 19°C it is transformed into a partially hexagonal crystal lattice, and the distance between the carbon atoms increases. This leads to a relatively large expansion with an expansion coefficient of up to 920 * 10-6/K. At 32°C there is a transition into an unordered structure. For comparison: the temperature coefficient of copper is 16.5*10-6/K.

The expansion coefficient shows that there is another phase change at 32.3°C. This is, however, much weaker and was not detected during the measurements in 1953. Only modern, much-improved instrumentation enabled this discovery.

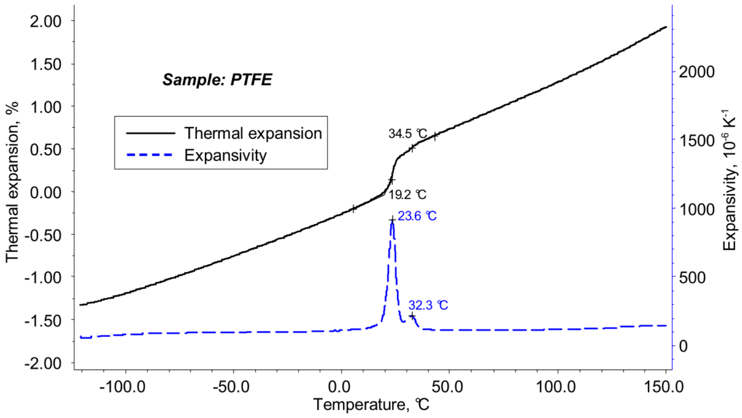


Fig. 1: Relative expansion of PTFE vs. temperature

The adjoining Fig. 1 is taken from [2]. Measured values were extracted from this diagram and used for further calculations.

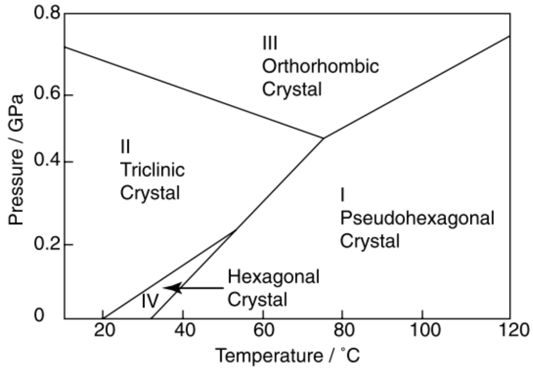


Fig. 2: Phase diagram of PTFE

Fig. 2 is taken from [3] and shows the basic phase diagram for PTFE. The relationship between tempera-ture, pressure and type of crystal lattice can be seen in the diagram. As pressure on PTFE increases, the temperature at which the change to lattice structure occurs also changes. It should be noted that the pressure shown is in the GPa-range, and is therefore rather high. As a comparison: the atmospheric pressure at sea level is only 0.101 MPa.

Moreover, the publications demonstrate that the properties of PTFE are also dependent on what has happened to it. For example: PTFE processed in a lathe and subsequently investigated resulted in slightly different values than PTFE which was heated to 300°C and then slowly cooled down before measuring.

In [8] (Koizumi) the dielectric constant of PTFE at 100 kHz and at various frequencies was measured. The values were extracted from the diagram and are subject to a margin of error in reading accuracy. The text states that the permittivity changes

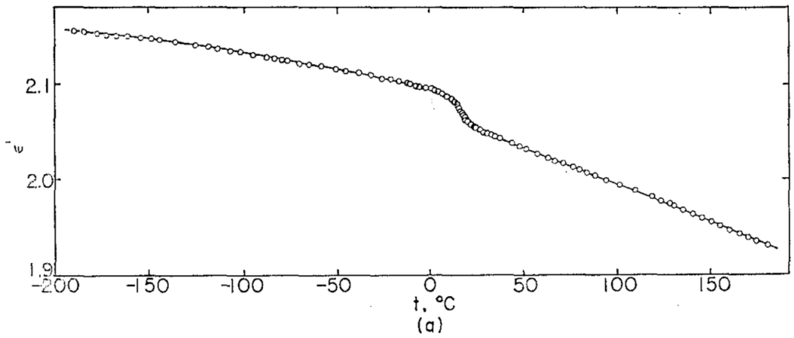


Fig. 3: Dielectricity constant vs. temperature

with the frequency from 2.1462 with DC to 2.1436 at in-finitely high frequencies. This is a change of merely 0.126% across the frequency range.

The coaxial cable

The outer shield of the coaxial cable is made of of metal and expands less than PTFE. The question here is how much the shield expands and how much pressure increase remains. This pressure increase com-pensates for the drop in the permittivity and can be calculated with an FEM simulation. However, it is all still dependent on time as PTFE will start to flow under pressure, i.e. if it is not possible to change the diameter, the material will try to expand lengthways.

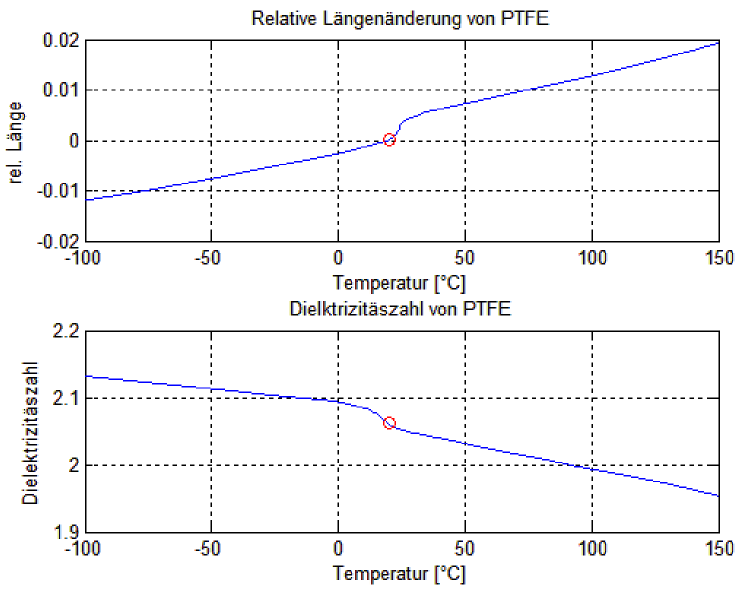


Fig. 4: Expansion and dielectricity constant taken from the extracted values

Moreover, the electrical length (i.e. the speed at which the electromagnetic wave travels along the ca-ble) is dependent on the permittivity, which in turn is dependent on temperature.

The relative length of the cable is shown in the upper graph of Fig. 4.

As can be seen, PTFE expands with increasing temperature, while the permittivity decreases. This does have a compensatory effect, but they do not fully counteract each other. So the question is: what will be the final change in electrical length?

In Part 2 of this series we will carry out our own measurements and calculations and compare them to existing publications partially described here.

Part 3 will conclude this PTFE-Information Series. It will concern itself with an FEM simulation of a coax-cable in which the pressure increase due to the shield – and thus the shift in crystallization – is consid-ered. The reslts of the simulation will be compared to coaxial cables which have already been measured. In addition, we plan to present the attenuation as soon as we have instrumentation for temperatures down to -100°C

Literature list:

[[1] Wikipedia, https://en.wikipedia.org/wiki/Polytetrafluoroethylene

[2] Characterization of PTFE using Advanced Thermal Analysis Techniques; J. Blumm, A. Lindenmann, M. Meyer, C. Strasse; Netzsch-Gerätebau GmbH

[3] The properties of poly(tetrafluoroethylene) (PTFE) in compression; P. J. Rae, D. M. Dattelbaum; Polymer 45 (2004) 7615 – 7625

[4] Molecular Mobility, Phase Transitions, Transformation Plasticity and Memory Effect in Poly(tetrafluo-roethylene) (PTFE); Journal de Physique III, Volume 6, dècembre 1996

[5] Transitions and Phase of Polytetrafluoroethylene (Teflon); C. E. Weir; Journal of Research of the Na-tional Bureau of Standards, Vol. 50, No. 2, February 1953

[6] Thermal Expansion of Polytetrafluoroethylene (Teflon) from -190° to +300°C; R. K. Kirby, ournal of Research of the National Bureau of Standards, Vol. 57, No. 2, August 1956

[7] Current Innovation in Phase Stable Coaxial Cable Design; Times Microwave Systems; Microwave Product Digist

[8] Understandign Effect of Teflon Room Temperature Phase Transition on Coax Cable Delay i Order to Improve the Measurement of TE Signals of Deuterated Polarized Targets; S. K. Dhawan; IEEE Transac-tions on nuclear sc.enge, Vol. 39, No. 5, October 1992

[9] Phase Drift Versus Temperature Measurmements of Coaxial Cables; K. Czuba, D. Sikora, Warsawa Uni-versity of Technology, ISE, Warsawa, Poland

[10] Low-Temperature Properties of Polymers, I. Perepechko, MIR Publishers, Moscow

[11] Microwave Measurement of Dielectric Properties of Low-Loss Materials by the Dielectric Rod Resona-tor Method; Y. Kobayashi, M. Katho; IEEE Transaction on microwave theory and techniques, Vol. MTT-33, No. 7, July 1985

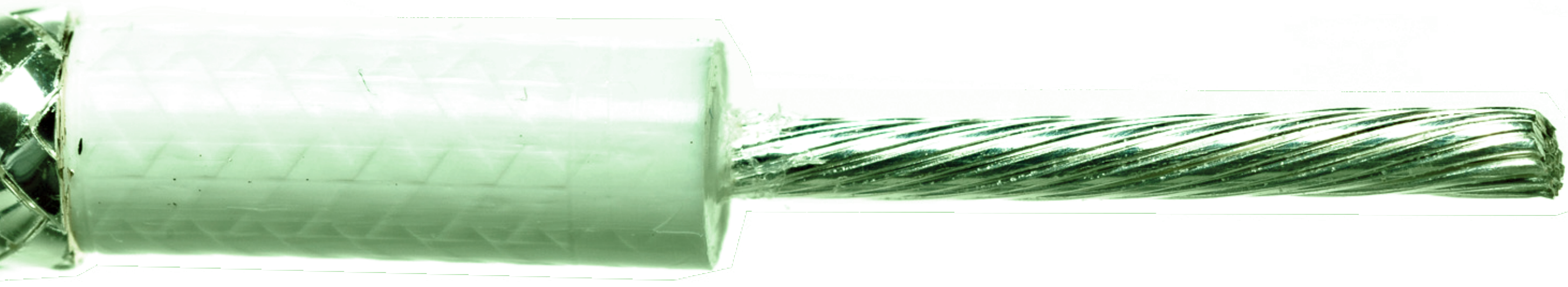
[12] Physical Properties of Fluon® unfilled and filled PTFE, Technical Service Note F12/13, AGC Chemicals 2002

Publishing Information

Concept, text & drawings: Stefan Burger, DeltaGamma RF-Expert, Melbourne Australien
Layout & design: Udo Klünsch | kpr kommunikation, Geretsried
Photos: Udo Klünsch | kpr kommunikation

el-spec GmbH
Lauterbachstr. 23c
82538 Geretsried-Gelting
T.: +49 8171 4357-0
F.: +49 8171 4357-99
sales@elspecgroup.de
Geschäftsführer: Thomas Weber
www.elspecgroup.de

1



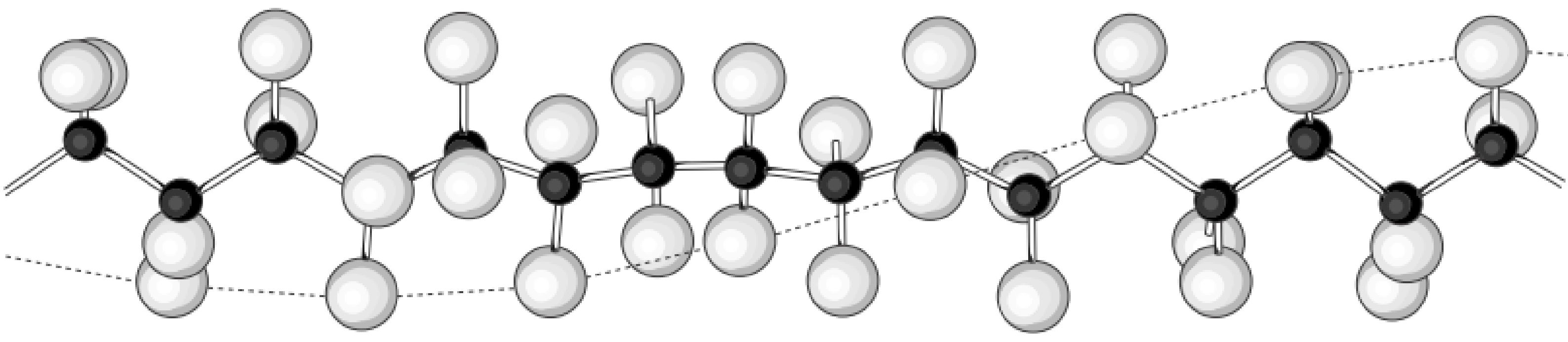
Facts about PTFE coaxial cables
Part 2

Dipl. Ing. (FH) Stefan Burger | DeltaGamma Consult

1.2 Facts about PTFE coaxial cables

Dipl. Ing. (FH) Stefan Burger | Delta Gamma RF-Expert

Content



Preface

For coaxial cables featuring low losses and a wide temperature range, for the role of the insulator primarily PTFE (polytetrafluorethylene) is employed. At elspect we see this as well: the most often ordered basic material over the last 32 years has been, next to copper, silver and steel, the insulating material PTFE. Requirements continue to become more and more stringent, and more exact as well as highly reproducible measurements are indispensable.

Therefore it is of particular concern for the RFspecialist elspec to give an overview regarding the state of research about and applications of PTFE, give insights about the properties and the limitations of this material, and summarize the various publications existing on these themes.

In the second part of our info-series about the most commonly used insulation material PTFE, we will compare – on the basis of of our own measurements and calculations – the behavior of the permittivity and change in length coupled to it.

We know that the electrical length of a line can be calculated with:

$$l_{el} = l \cdot \sqrt{\varepsilon_r} \qquad\qquad l = l_0(1 + TK_{PTFE} \cdot \Delta T)$$

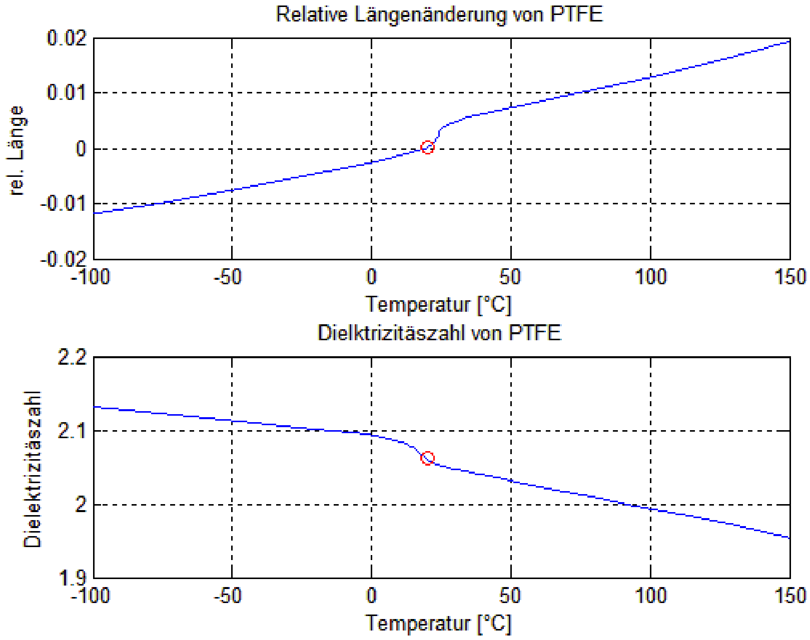


Fig 1: Expansion and dielectric constant taken from the extracted values

Accordingly, PTFE expands with rising temperature while the permittivity decreases. This does have a compensatory effect but not to the extent that the two changes cancel each other out.

Let us consider now the change over temperature for a coaxial line purely mathematically according to the following formula:

$$\Delta l = l \cdot \sqrt{\varepsilon r(T)} \cdot (1 + TK \cdot \Delta T) - l \cdot \sqrt{\varepsilon r(20°C)}$$

Δl : elongation
l : mechanical length of the line
$\varepsilon r(T)$: temperature-dependent permittivity
ΔT : Temperature change

Below 0°C, the electrical length remains substantially constant while it decreases at higher temperatures - by 10mm at 100°C. Within the temperature range of

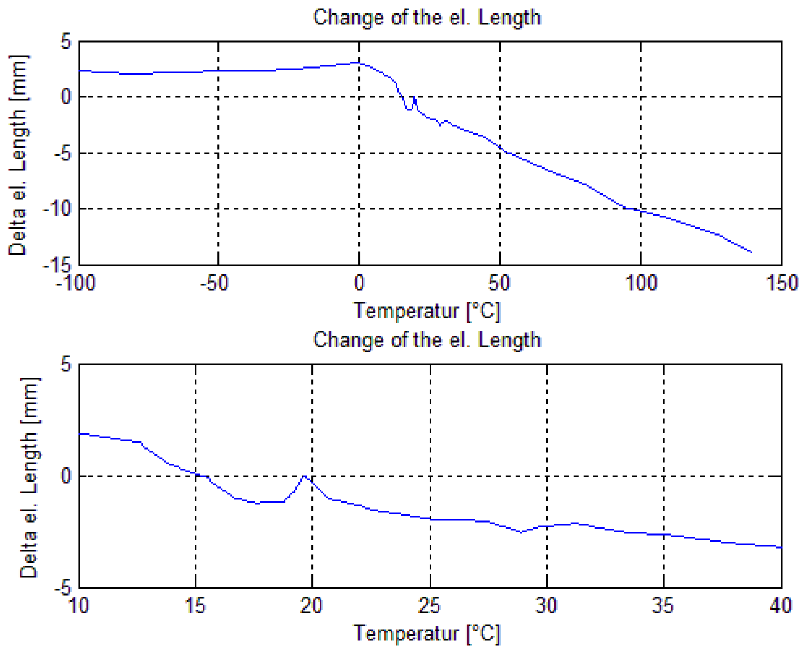


Fig. 2: Change of the electrical length vs. temperature

10°C to 40°C the reduction is about 5mm corresponding to a phase change of 6° at 1GHz and 60° at 10GHz. However, this results needs to be viewed with caution since the values for the material properties are taken from different publications and thus from two different samples.

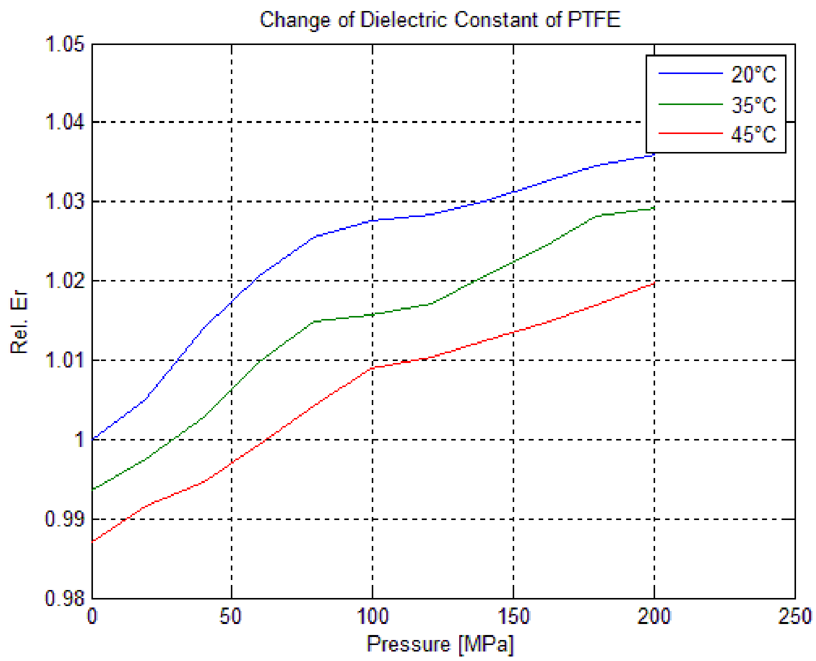


Fig 3: Relative permittivity of PTFE depending on pressure and temperature

The crystalline phase-change is dependent on pressure, as well. The values in Fig. 3 are taken from [13]; as can be seen, the permittivity increases with mounting pressure. Since PTFE expands more strongly than the copper shielding, and since for some cables a second shield is made from stainless steel, a pressure builds up chic counteracts the drop in permittivity an thus also the change in length.

In oder to obtain an estimate for the resulting pressure, we can use –for a tubular object - the pipe formula. WE will assume that the material is only loaded within its elasticity limits i.e. the stress needs to remain below the yield point which for copper is in the range of 120 – 320 N/mm2.

$$\mathrm{P} = \frac{\sigma_t \cdot 2 \cdot s}{d_m}$$

P : pressure
σ_t : tangential tension
s : shield thickness
d_m : average diameter of the shield

For a coaxial line with a diameter of 1.19mm we calculate the result of the equation to a maximum pressure of about 75 MPa. Fig. 3 gives a permittivity increase of about 1.5% compared to the state when no pressure is exerted. If this is considered during the design process it is possible to minimize the resulting phase change; however, it will require an FEM simulation for calculating and optimizing the multi-physical problem. Despite this effort, it will not be possible to fully compensate the changes. Between 10°C and 40°C a more or less pronounces jump will remain.

To further minimize the effect, one may try to reduce the share of the dielectric. This could be done e.g. by holding the inner conductor in place in the centre of the shield via using dielectric supports with periodic spacing, or spirals, or other designs. Another possibility would be to increase the proportion of air within the dielectric. PTFO foam would see to be a very good solution – however at present industrial production of this material seems not to be possible.

If PTFE is stretched cold, very small pores appear in the material. The Gore company uses this process. Both approaches reduce the effective permittivity. The result is a smaller phase distortion and also a reduction of the dielectric losses.

Literature list:

[1] *Wikipedia, http://de.wikipedia.org/wiki/Polytetrafluorethylen*

[2] *Characterization of PTFE using Advanced Thermal Analysis Techniques; J. Blumm, A. Lindenmann, M. Meyer, C. Strasse; Netzsch-Gerätebau GmbH*

[3] *The properties of poly(tetrafluoroethylene) (PTFE) in compression; P. J. Rae, D. M. Dattelbaum; Polymer 45 (2004) 7615 – 7625*

[4] *Molecular Mobility, Phase Transitions, Transformation Plasticity and Memory Effect in Poly(tetrafluoroethylene) (PTFE); Journal de Physique III, Volume 6, dècembre 1996*

[5] *Transitions and Phase of Polytetrafluoroethylene (Teflon); C. E. Weir; Journal of Research of the National Bureau of Standards, Vol. 50, No. 2, February 1953*

[6] *Thermal Expansion of Polytetrafluoroethylene (Teflon) from -190° to +300°C; R. K. Kirby, ournal of Research of the National Bureau of Standards, Vol. 57, No. 2, August 1956*

[7] *Current Innovation in Phase Stable Coaxial Cable Design; Times Microwave S ystems; Microwave Product Digist*

[8] *Understandign Effect of Teflon Room Temperature Phase Transition on Coax Cable Delay in Order to Improve the Measurement of TE Signals of Deuterated Polarized Targets; S. K. Dhawan; IEEE Transactions on nuclear sc.enge, Vol. 39, No. 5, October 1992*

[9] *Phase Drift Versus Temperature Measurmements of Coaxial Cables; K. Czuba, D. Sikora, Warsawa University of Technology, ISE, Warsawa, Poland*

[10] *Low-Temperature Properties of Polymers, I. Perepechko, MIR Publishers, Moscow*

[11] *Microwave Measurement of Dielectric Properties of Low-Loss Materials by the Dielectric Rod Resonator Method; Y. Kobayashi, M. Katho; IEEE Transaction on microwave theory and techniques, Vol. MTT-33, No. 7, July 1985*

[12] *Physical Properties of Fluon® unfilled and filled PTFE, Technical Service Note F12/13, AGC Chemicals 2002*

[13] *Effects of Temperature and Pressure on the Dielectric Constant in Non-Polar P olzmers; H. Sasabe, S. Saito, Polzmer Journal, Vol. 3, No. 6, 1972*

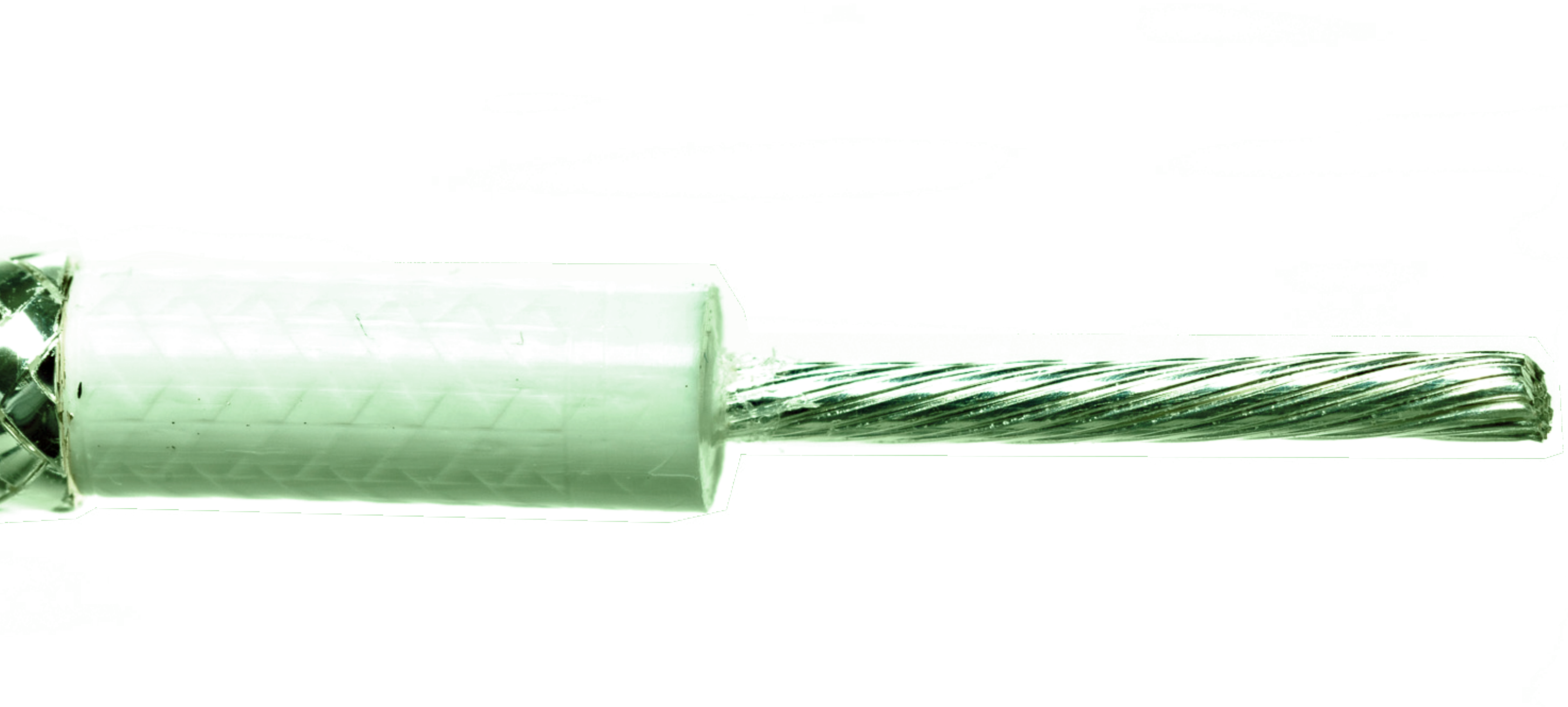
Legal

Concept, text & drawings: Stefan Burger, Delta Gamma RF-Expert, Melbourne Australien
Layout & design: Udo Klünsch | kpr kommunikation, Geretsried
Photos: Udo Klünsch | kpr kommunikation

el-spec GmbH
Lauterbachstr. 23c
82538 Geretsried-Gelting
T.: +49 81 71 43 57-21/-22
F.: +49 81 71 43 57-99
info@elspegroup.de
Managing director: Thomas Weber
www.elspecgroup.de

1.3

elspec group GmbH



Facts to know about PTFE in RF-technology

Part 3

Dipl. Ing. (FH) Stefan Burger | DeltaGamma Consult

1.3 Facts to know about PTFE in RF-technology

Part 3

Dipl. Ing. (FH) Stefan Burger | DeltaGamma RF-Expert

Inhalt

Introduction

As already mentioned in the two previous articles, the properties of PTFE are dependent on its prior „history" i.e. how it was treated in the past. The simultaneous measurement of both permittivity and expansion against temperature therefore is of importance. As will be shown later, this influence in not insignificant – using data from different (i.e. non-simultaneous) series of measurements may lead to inaccurate or even false results (see Part II). An extensive search did not yield any literature showing results of both permittivity and expansion of PTFE measured at the same time; we consequently put together a test-setup and measured various samples.

Polytetrafluorethylen

Polytetrafluorethylen ist ein unverzweigtes, linear aufgebautes, teilkristallines Polymer aus Fluor und Kohlenstoff. Umgangssprachlich wird dieser Kunststoff oft mit dem Handelsnamen Teflon der Firma DuPont bezeichnet. Weitere häufig verwendete Handelsnamen anderer Hersteller von PTFE sind Dyneon PTFE und Gore-Tex für PTFE-Membranen.
Wikipedia (DE)

1 - Test setup

To measure the permittivity, there are various approaches to a setup – with associated advantages and disadvantages. Since PTFE has no strong dependency on frequency, and since losses are low, a resonator may serve as a test-structure. The sample is positioned within the maximum electrical field to achieve highest sensitivity. Comparative simulations with square and round resonators indicated that the round resonator had, at the same resonance frequency, a slightly better Q-factor when without load. This meant a higher sensitivity at low dielectric losses.

To measure the change in length, a laser-based triangulation device (for distance measurements) HL-G103 made by Panasonic was deployed. It features a resolution of 0.5 µm and a measurement accuracy of ± 0.2 % in the measurement range of 2 mm, as long as it is kept at constant temperature during the measurements. Since the device was placed in a temperature chamber operated between 0°C and 45°C, there was a larger deviation which was, however, reproducible. With the aid of a reference measurement, this influence could be subtracted out and was eliminated.

Fig. 1 shows the resonator with the distance sensor positioned above the sample. The cavity has a diameter of 78.8 mm and a height of 30 mm. The effective resistance of the wall has an impact on the Q-factor because current flows from the base to the lid. It was shown in

[1] that rounding-off the sharp angles at the base and at the lid leads to a 5% improvement of the Q-factor..

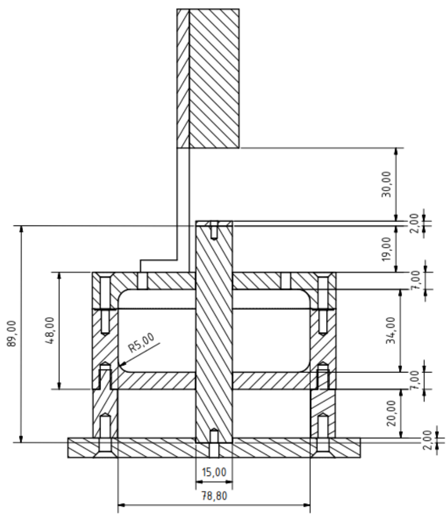


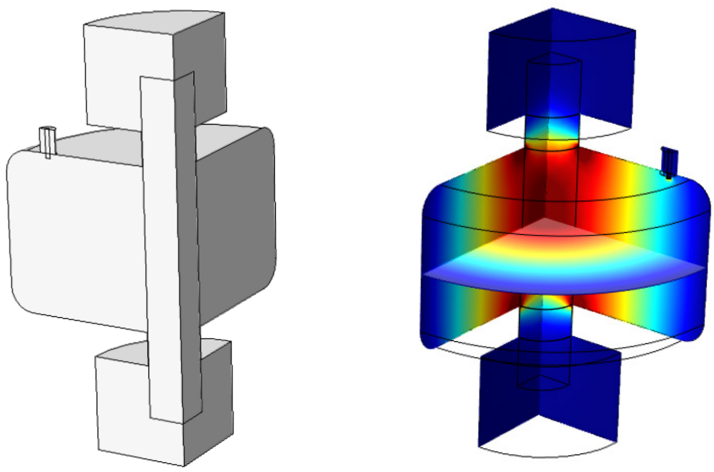
Abb 1: setup for testing

PTFE shows up as white plastic; this colour, however, is the result of a diffuse reflection at the sintered PTFE powder. The first measurements showed unstable or illogical results, with the position of the reflection changing with the temperature. For this reason, a small metal plate was bolted onto the sample, stabilizing the measurement. To ensure that the sample remains on the base of the resonator, it was bolted down. These measures, at last, enabled us to achieve stable results.

2 - Simulation-model

The resonator including the sample was implemented in Comsol Multiphysics as a full-, half- and quarter-model. Extensive simulations were carried out to see whether differences between the simulations showed up. Another aspect was whether the positioning of the sample exactly in the middle and perpendicularly, or off-centre, or tilted, would have an influence. Since the sample is required to have a smaller diameter than the drill-hole, a non-ideal positioning was a possibility. It was found, however, that there was no influence of these parameters on the measurement, and the calculations were done for a centric position of the sample, and for a quarter-resonator.

Outside of the resonator, the sample protrudes into open space. Part of this area was included into the model. The size of the open area above and below the resonator was dimensioned such that for the resonance condition, the field had levelled-off by at least 60 at the edges. This was to ensure that no frequency detuning could occur due to the limited free space.



(a) Model *(b) E-Field*

Abb 2: quarter-model and electric field-distribution

With the nominal diameter, we found a discrepancy with the measured values. The diameter was optimized such that the dependency of the resonance frequency on the temperature matches the measurement. In the end, the deviations were within ±3 kHz.

3 - Measuring setup and measurements

The resonator was operated in a temperature chamber in the range from 5°C to 45°C. It was connected to a network analyzer (VNA) that recorded the S-parameters under program.-control in regular intervals. Simultaneously (i.e. in parallle), the distance-measurement device was read out and the temperature was documented, as well.

For the first measurements, the results suffered from strong noise caused by the vibrations of the compressor of the temperature chamber. To circumvent this problem, a temperature of 5°C was set and maintained for 30 min. The chamber was then switched off such that the interior heated up with time. Later, a heating resistor was added in to achieve 45 °C.

The resonance curve read out by the VMA did not have the resolution necessary to reliably determine small frequency changes. The measurements were therefore matched to a Lorentz-function, and the resonance frequency and the bandwidth were extracted from it. The Q-factor with load (1) was calculated from the resonance frequency and the bandwidth. Using the insertion-loss, the Q-factor for the condition without load (2) was then also calculated.

$$Q_L = \frac{f_0}{B} \tag{1}$$

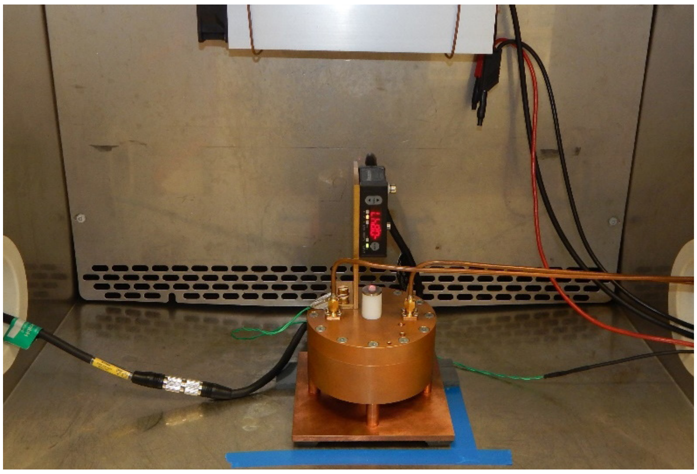


Abb 3: temperature chamber with resonator

$$Q_u = \frac{Q_L}{1 - 10^{\frac{IL[dB]}{20}}} \tag{2}$$

For the closed resonator (without drill holes in the base and the lid), the Q-factor can be calculated for the various modes. In our case it was the TM010-mode using equation (3).

$$Q_{010} = \frac{Z_0 \cdot j_{01}}{R_s \cdot 2 \cdot (\frac{R(T)}{H(T)} + 1)} \tag{3}$$

$$R_s = \sqrt{\frac{\omega_0 \cdot \mu_0}{2 \cdot \sigma(T) \cdot \sigma_r}} \tag{4}$$

$$\sigma(T) = \sigma_0 \cdot (1 + \alpha \cdot (T - T_0)) \tag{5}$$

$$Z_0 = \mu_0 \cdot c \tag{6}$$

For the radius R and the height H, the temperature coefficient for the length variation was calculated from $16.5 \cdot 10^{-6} \frac{1}{K}$ of the ideal conductance of copper with $58.5 \cdot 10^{-6} \frac{S}{m}$ and $\alpha = 3.9 \cdot 10^{-3} \frac{1}{K}$. Z_0 is the wave impedance in free space and j_{01} is the zero of the Bessel function for the TM01 mode with 2.405. The curves for measured and calculated Q-factor do agree rather well (Fig. 4), considering that the equation is fully exact only for closed resonators.

The non-ideal conductance due to the surface roughness is considered via the relative conductance that can be calculated, using equation (7), from the Q-factor without load

.

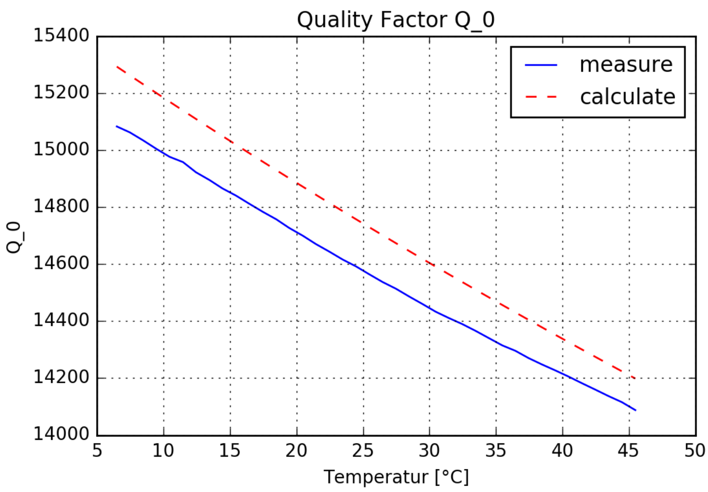


Abb 4: measured and calculated Q-factor of the empty resonator

$$\sigma_r = \left(Q_u \cdot \frac{\delta_{s0}}{\lambda} \cdot \frac{2 \cdot \pi \cdot \left(1 + \frac{D(T)}{2 \cdot H(T)}\right)}{j_{01}} \right)^2 \tag{7}$$

$$\delta_{s0} = \sqrt{\frac{1}{\pi \cdot f \cdot \mu_0 \cdot \sigma(T)}} \tag{8}$$

Estin [3] has investigated the impact of the drill holes in lid and base on the resonance frequency. This influence is considered via a correction factor that Estin determines by rigorous analysis. In our case, it was determined using the field simulation in which for each temperature, the permittivity and the losses were optimized until they matched the measurements.

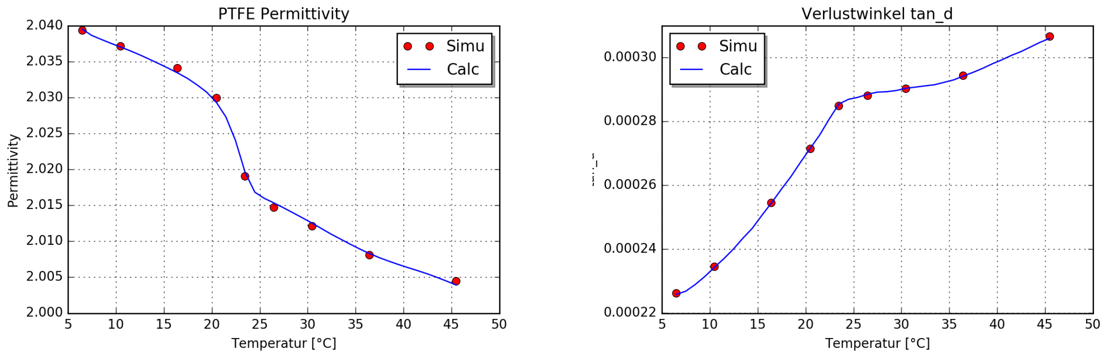
$$\epsilon_r = C_1 \cdot 2 \cdot J_1(j_{01})^2 \cdot \frac{f_0 - f_1}{f_1} \cdot \left(\frac{D(T)}{d(T)}\right)^2 + 1 \tag{9}$$

$$tan\delta = C_2 \cdot \frac{2 \cdot J_1(j_{01})^2}{\epsilon_r} \cdot \left(\frac{D(T)}{d(T)}\right)^2 \cdot \left(\frac{1}{Q_{DUT}} - \frac{1}{Q_0}\right) \tag{10}$$

$$C_1 = 1.05913 - 7.33 \cdot 10^{-5} \frac{1}{{}^\circ C} \cdot T[{}^\circ C] \tag{11}$$

$$C_2 = 1.20974 - 4.963 \cdot 10^{-4} \frac{1}{{}^\circ C} \cdot T[{}^\circ C] \tag{12}$$

J_1 : 1st-order Bessel function
D(T) : temperature dependent diameter of the resonator
d(T) : temperature dependent diameter of the sample
Q_{DUT} : Q-factor with sample, no load
Q_0 : Q-factor of resonator, no load



(a) Permittivity

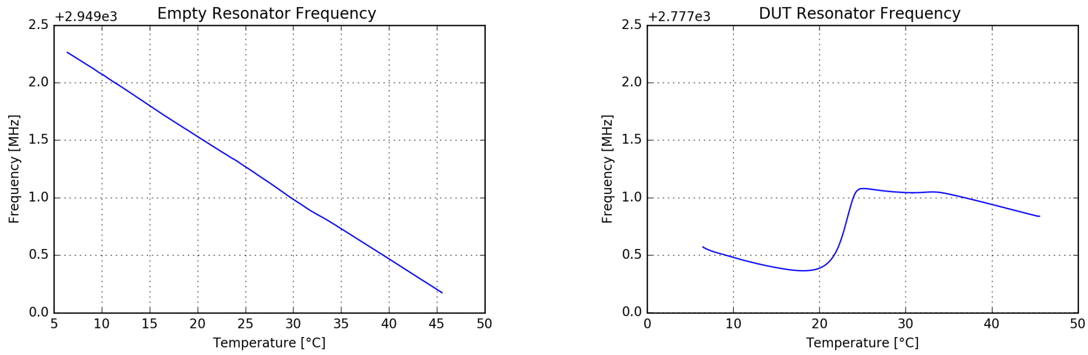
(b) dielectric losses

Abb 5: Comparison field simulation and calculation

Applying the correction factor, the calculation agrees very well with the results of the field-simulation.

3.1 - Measurement with PTFE

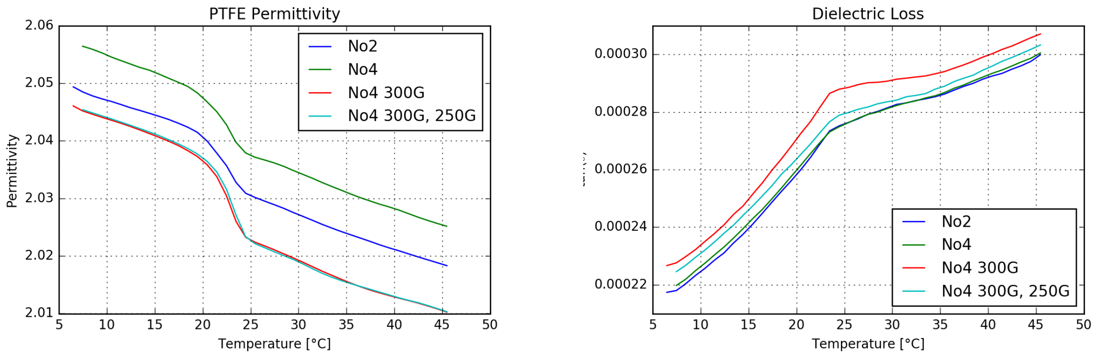
With the PTFE sample installed, the temperature drift of the resonance frequency is smaller that without the sample (Fig. 6). This was to be expected given the fact that with rising temperature, the permittivity decreases and counteracts the drift caused by the resonator expansion.



(a) empty (b) with sample

Abb 6: Resonance frequency without and with sample

After tempering, sample no. 4 was shorter with the diameter having increased. The sample was therefore machined again. To make sure that the properties were not changed by this process, it was again heated to 250°C for an extended period of time. This did not reveal any differences in the permittivity; the dielectric losses, however, were at a slightly lower level. This might have resulted from remaining air humidity.



(a) Permittivity (b) tan(δ)

Abb 7: Permittivity and tan(δ) of different samples

This memory effect is caused by mechanical tensions within the PTFE that occur during manufacture or machining. As the PTFE is heated up to 340°C for an extended period of time, and then slowly cooled down, the molecule-chains can orient themselves unimpeded.

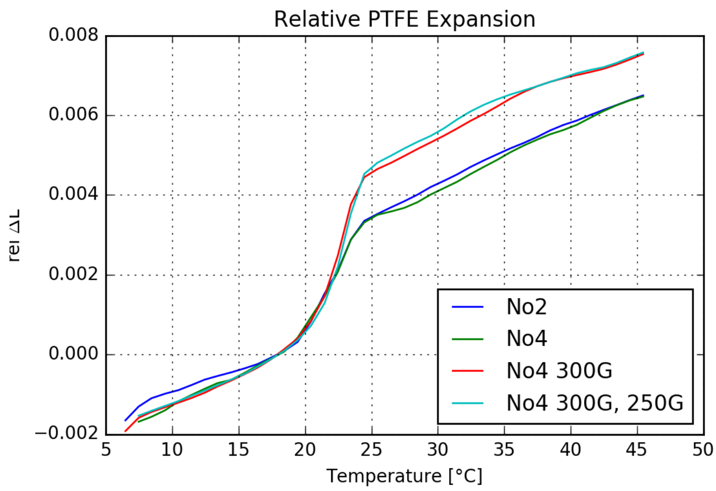
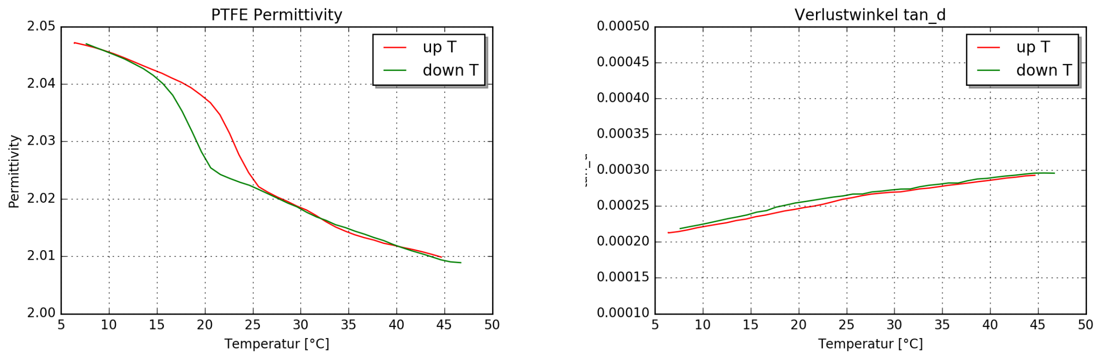


Abb 8: Relative expansion of different samples

3.2 - Hysteresis

As noted already earlier, the PTFE-characteristics move along a hysteresis-curve as the temperature is varied around the step. For this reason, sample no. 4 was measured again from 5°C to 45°C, and then back to 5°C. Running the temperature from high to low, the step shifts by 4°C towards lower temperatures, resulting in a maximum permittivity difference of 0.0125 or 0.6%. For the losses, no change can be seen. The visible difference results from the measurement uncertainty.



(a) Permittivity *(b) tan(δ)*

Abb 9: Permittivity and tan(δ) over temperature cycle

4 - Comparison: calculation vs. measurement

Using the measured permittivity and expansion of the PTFE, it is now possible to calculate how the properties of a coaxial line change with temperature.

4.1 - Impedance

The impedance of a coaxial line is calculated as follows:

$$Z_L = \frac{\mu_0 \cdot c}{2 \cdot \pi} \cdot \frac{1}{\sqrt{\epsilon_r(T)}} \cdot \ln \frac{D(T)}{d(T)} \tag{13}$$

Z_L : impedance
μ_0 : magnetic field constant $4 \cdot \pi \cdot 10^{-7} \frac{N}{A^2}$
c : speed of light 299 792 458 m/s
$\varepsilon_r(T)$: relative permittivity of the dielectric
D(T) : diameter of the shield
d(T) : diameter of the inner conductor

If the inner conductor and the shield are made from the same material, the ratio remains the same, and so does the impedance. In such a line, the permittivity has the significant influence.

Assuming that the PTFE can expand in length, the impedance can be calculated ignoring pressure exerted onto the PTFE.

If expanded PTFE is used, the influence decreases, since the effective permittivity is smaller. The share of air can be determined from the propagation velocity in the line.

$$\frac{v}{c} = \frac{1}{\sqrt{\epsilon_r}} \tag{14}$$

$$a = \frac{\left(\frac{c}{v}\right)^2 - \epsilon_{r\_PTFE}}{\epsilon_{r\_Air} - \epsilon_{r\_PTFE}} \tag{15}$$

a : share of air
$\frac{v}{c}$: relative propagation velocity
ε_{r-PTFE} : relative permittivity of PTFE
ε_{r-Air} : relative permittivity of air

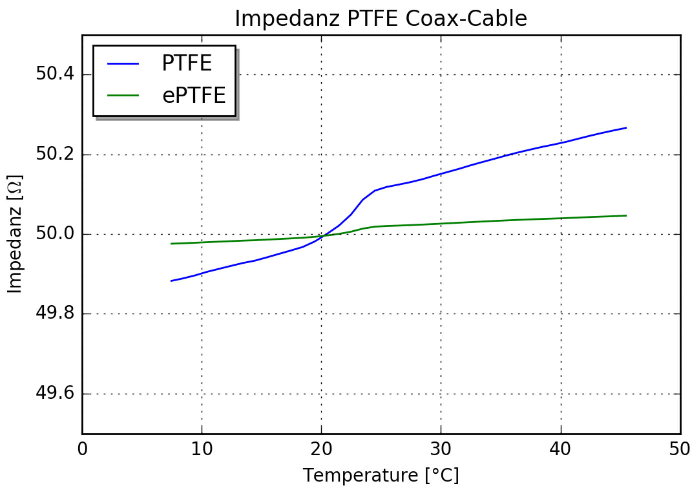


Abb 10: Impedance dependent on temperature

Considering manufacturing tolerances, a high-quality coaxial line has an impedance of (50 ± 2) Ω. The influence of PTFE is significantly smaller than the manufacturing tolerance: for a coaxial line with PTFE it is about (50 ± 0.3) Ω and for one with ePTFE it is (50 ± 0.03) Ω.

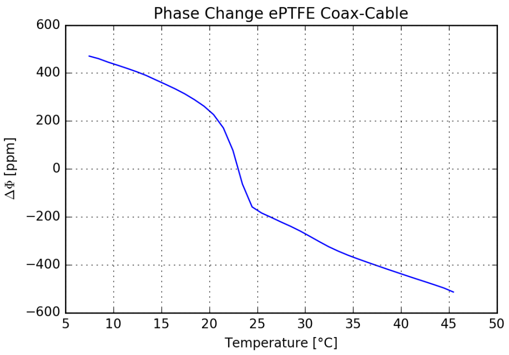
4.2 - Phase stability

The behaviour of PTFE under pressure is problematic [5]. The permittivity rises as pressure is applied to PTFE. Since there are no exact data, an FEM simulation will only give inaccurate results, as well. For a coaxial cable including expanded PTFE, the situation is a bit different. The assumption is that, as the PTFE expands, the share of air is correspondingly reduced. Inner conductor and shield will expand according to their temperature coefficients, and will define the available space. Variations in the permittivity will show up most prominently in the phase stability, for which specifications are available in data sheets for some cable types.

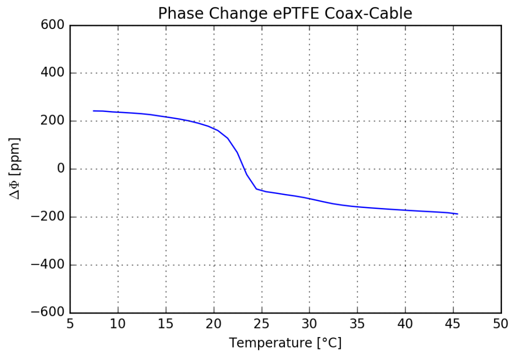
$$\Phi = \frac{l}{\lambda} \cdot 360^\circ \tag{16}$$

$$\Delta\Phi = \frac{\Delta\varphi}{\Phi} \cdot 10^6 \, [ppm] \tag{17}$$

The Phase Master cable by Teledyne Storm features a phase-stability value of max. 865 ppm, and a relative propagation velocity of 0.87. The comparison of the phase stability of such a phase-optimized cable and a corresponding calculation is shown by Fig. 11a. The phase change is in the same order of magnitude but has a different characteristic. The simplified assumption seems to disregard essential influences. As the PFTE-share is reduced further such that the relative propagation velocity is 0.91, the calculation does show a behaviour similar to what is depicted in the data sheet. The phase change reaches a maximum and a minimum value as given in Fig. 11b.



(a) relative propagation velocity 0.87



(b) relative propagation velocity 0.91

Abb 11: Change of phase dependent on temperature

Summary

Due to its large temperature range, the relatively stable permittivity, and the least losses amongst the whole group of polymers, PTFE is one of the most significant synthetics for applications in RF. Disadvantageous is the memory effect which can make the properties vary from sample to sample, and its hysteresis. In order to consider these effects, exact data are required. The latter can only be gathered by simultaneously measuring permittivity and expansion.

Literature list:

[1] M. Höft, S. Burger*, Q-factor improvement of combline resonators,* German Microwave Conference 2005, Ulm, Germany, pp. 53-56, 5.-7. Apr. 2005*.*
[2] S. Ramo, J. R. Whinny, T. van Duzer: *Fields and Wave in Communication Electronics,* 3rd Edition, Wiley
[3] A. J. Estin, H. E. Bussy, *Errors in dielectric measurements due to a sample insertion hole in cavity,* IRE *Transactions on Microwave Theory and Techniques,* pp. 650-653, November 1960
[4] H. Kawabata, H. Tanpo, Y. Kobayashi*: An Improvement of the Perturbation Method Using a TM010 Mode Cylidrical Cavity,* IEICE Trans. Electron., Vol. E86-C, No. 12 Dec 2003
[5] H. Sasabe, S. Saito, *Efects of Temperature and Pressure on the Dielectric Constant in Non-Polare Polymers,* Polymer Journal, Vol. 3, No. 6, 1972

Legal

Concept, text & drawings: Stefan Burger, Delta Gamma RF-Expert, Melbourne Australien
Layout & design: Udo Klünsch | kpr kommunikation, Geretsried
Photos: Udo Klünsch | kpr kommunikation

el-spec GmbH
Lauterbachstr. 23c
82538 Geretsried-Gelting
T.: +49 81 71 43 57-21/-22
F.: +49 81 71 43 57-99
info@elspegroup.de
Managing director: Thomas Weber
www.elspecgroup.de

Notes

Notes

Notes

el-spec GmbH
Lauterbachstr. 23c
82538 Geretsried-Gelting, Germany
Tel. +49 (0) 8171 4357-23
Fax +49 (0) 8171 4357-99
E-Mail: info@elspecgroup.de
www.elspecgroup.de