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Coaxial Cables – Build and Use

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

About the author

Stefan Burger received his engineering degree from the Offenburg University of Applied Science in 1986. He remained as a research associate at the university until 1990. He then transferred to the research and development department of Endress + Hauser in Maulburg.

Until 2001, he was involved in the development of level measuring devices based on RADAR. Among other things, he was responsible for the support of the RADAR modules as well as the development of antennas and pressure-resistant RF components.

From 2001 to 2011, he worked on filters and duplexers for base stations as well as SAW filters at Panasonic Electronic Devices in Lüneburg. He was responsible for the "Lifetime and Power Durability" simulation.

In 2012, he founded his own company, Delta Gamma Consultant (www.delta-gamma.com), in Hampton, Australia. From 2014 he has been working for el-spec GmbH as exclusive advisor in the area of RF-technology and instrumentation, and in October 2017 he became a team member of the elspec group, assuming the role of Senior RF Engineer.

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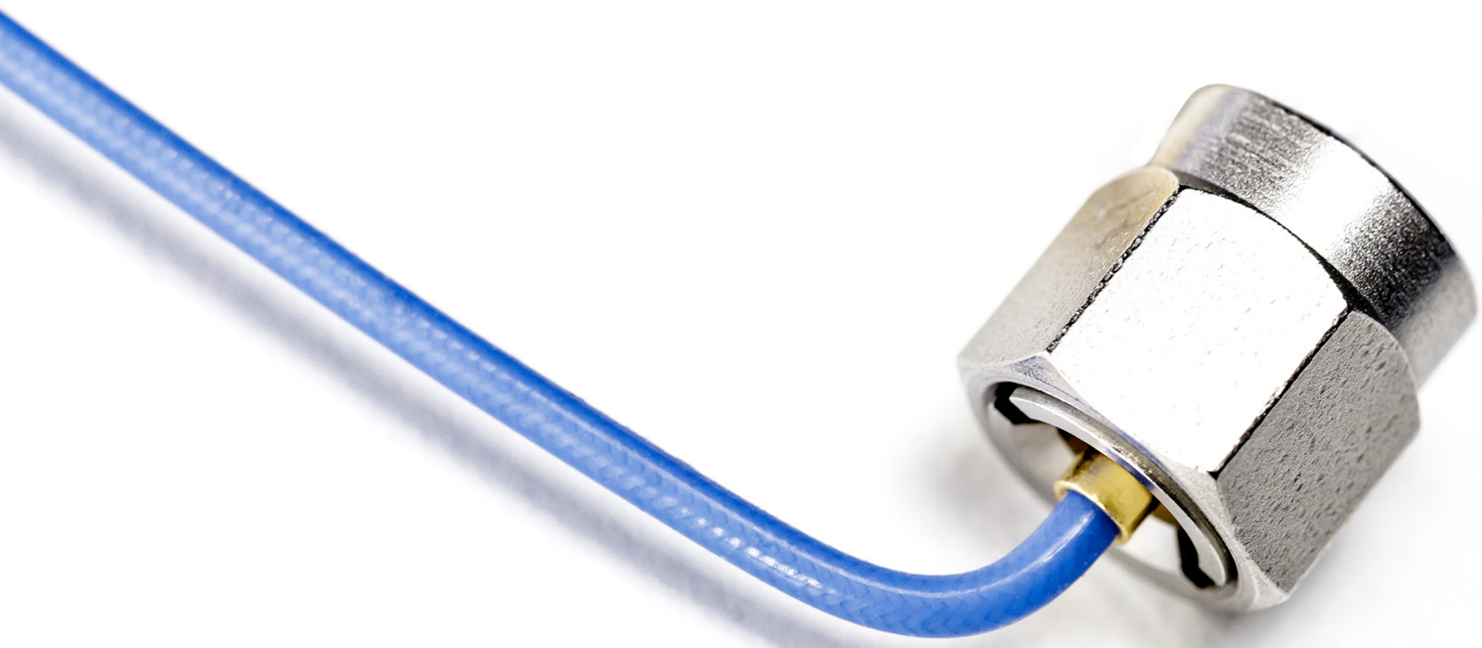
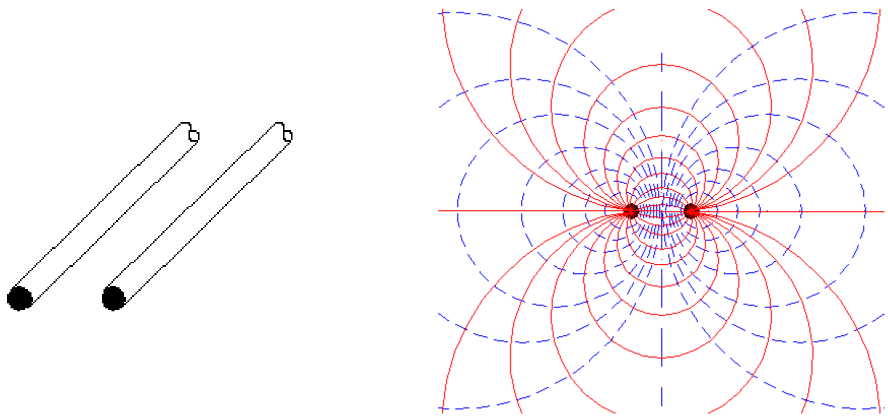


Angled connector? Not necessary!

Introduction

To connect signals from A to B one may use, for example, two parallel wires. In fact, this does work up into the HF-range if we keep our eyes on the impedance of this two-wire line. Disadvantageous is, however, that the field propagates around the wires and that everything coming close will have an impact on the transmission properties.

Waveguides, on the other hand, carry the electro-magnetic field inside a metal tube. What happens externally has no impact on the field. The disadvantage here is that there is a minimum frequency from which the energy transport is in fact possible. Moreover, such a conductor is very stiff and may not be bent easily.



(a) Two-wire line (b) Field

Fig. 1 Two-wire line and its electro-magnetic field

Placing one of the two conductors of the two-wire line concentrically around the other yields a coaxial line. The field is guided between the two conductors and remains independent of what is happening outside. In order to keep the following equations clear and accessible, we assume for our further consideration that the line has no magnetic component ($\mu r=1$).

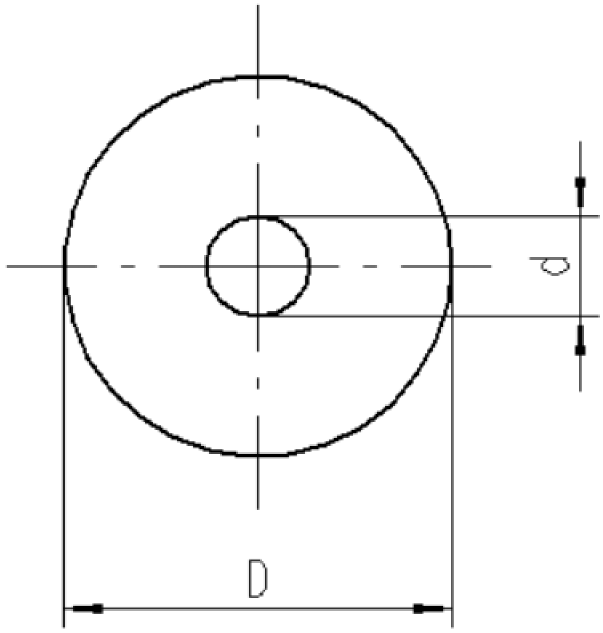


Fig. 2 : Cross-section through a coaxial line

1 Impedance

The impedance of a coaxial cable is calculated according to equation (1).

$$Z_L = \frac{Z_0}{2 \cdot \pi \cdot \sqrt{\epsilon_r}} \cdot \ln \frac{D}{d} \tag{1}$$

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} \tag{2}$$

$$\epsilon_0 = \frac{1}{\mu_o \cdot c_0^2} \tag{3}$$

Replacing the open-space wave impedance and the electrical field constant with equations (2) and (3) gives us equation (4)

$$Z_L = \frac{\mu_0 \cdot c_0}{2 \cdot \pi \cdot \sqrt{\epsilon_r}} \cdot \ln \frac{D}{d} \tag{4}$$

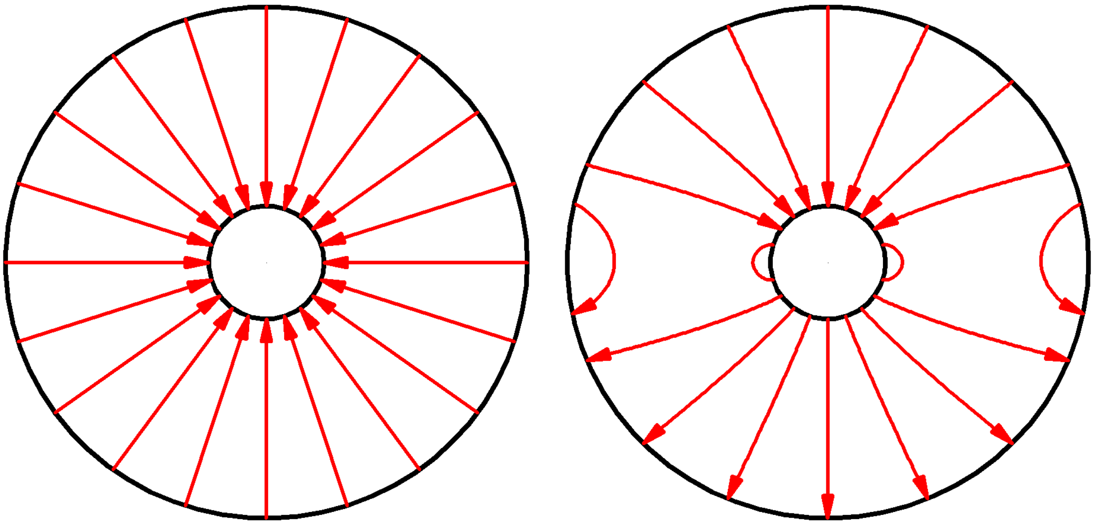
Inserting the values it yields the approximative equation (5). The error made is about 0,7 • 10-3 which in most cases represents a sufficient accuracy.

$$Z_L \approx \frac{60\Omega}{\sqrt{\epsilon_r}} \cdot \ln \frac{D}{d} \tag{5}$$

Z_L : impedance of the line
μ_0 : magnetic field constant $4 \cdot \pi \cdot 10^{-7} \frac{N}{A^2}$
c_0 : speed of light 299 792 458 m/s
ε_r : relative permittivity of the dielectric
D : diameter of the shielding
d : diameter of the inner conductor

The impedance is an important consideration because a part of the power is reflected if the line is not terminated with the characteristic impedance. The reflected power may cause faults in the system or, if it is too big, even damage of parts of it.

A matching of 10 dB means that 10% of the power is reflected. For 20 dB this drops to 1%.



(a) TEM-Mode (b) TE11-Mode

Fig. 3 Electrical field for the TEM and TE11 Modes

The field in the within the line assumes a TEM mode configuration, and does not have a lower cut-off frequency i.e. the cable may be used for DC, as well. As the wavelengths become smaller, the next-higher mode – the TE11 mode – may propagate. It is calculated [1] with the equation (9) using the solution of the transcendental equation (6). We find the x for which equation (6) for the first time assumes the value of 0.

$$\Big(J_0(x \cdot A) - J_2(x \cdot A)\Big) \cdot \Big(Y_0(x) - Y_2(x)\Big) - \Big(Y_0(x \cdot A) - Y_2(x \cdot A)\Big) \cdot \Big(J_0(x) - J_2(x)\Big) = 0 \quad (6)$$

$$A = \frac{R}{r} \quad (7)$$

$$f_c = \frac{x \cdot c_0 \cdot (A+1)}{(R+r) \cdot 2 \cdot \pi \cdot \sqrt{\epsilon_r}} \quad (8)$$

J_n : first-order Bessel function
Y_n: second-order Bessel function
R : radius of shielding
r : radius of inner conductor

A further important characteristic is the propagation velocity, which for the coaxial cable is dependent of the permittivity of the dielectric. As long as the permittivity remains constant over frequency, the propagation velocity is constant, as well. It is smaller than the speed of light, and therefore the line appears longer electrically than it is mechanically.

$$v = \frac{c_0}{\sqrt{\epsilon_r}} \quad (9)$$

2 Attenuation

The attenuation of a coaxial line results from the resistive component and the losses in the dielectric. In the following the individual contributions are analyzed and their contribution is individually represented in order to obtain a better understanding.

2.1 Resistive attenuation

The ohmic losses of the shield and of the inner conductor contribute to the attenuation with different strengths. In practice, different metals are used so that these are considered in the equations.

With increasing frequency, the current is pushed from the inside of the conductor to the surface. The corresponding penetration depth depends on the conductance and becomes noticeable already at relatively low frequencies. For example, for copper it is approximately 66μm at 1 MHz. For an inner-conductor diameter of 1 mm and considering 5 times the penetration depth, no significant current remains in the interior of the conductor. For the sheet resistance, it is assumed that a conductor has no thickness but the same value as a conductor that has only the thickness equal to the penetration depth of the current (10).

$$R_S = \sqrt{\frac{\pi \cdot f \cdot \mu_0 \cdot \mu_r}{\sigma}} \tag{10}$$

Dividing this value by the circumference yields the resistance with consideration of the current displacement. In equations (11) and (12), this has been done separately for shield and inner conductor.

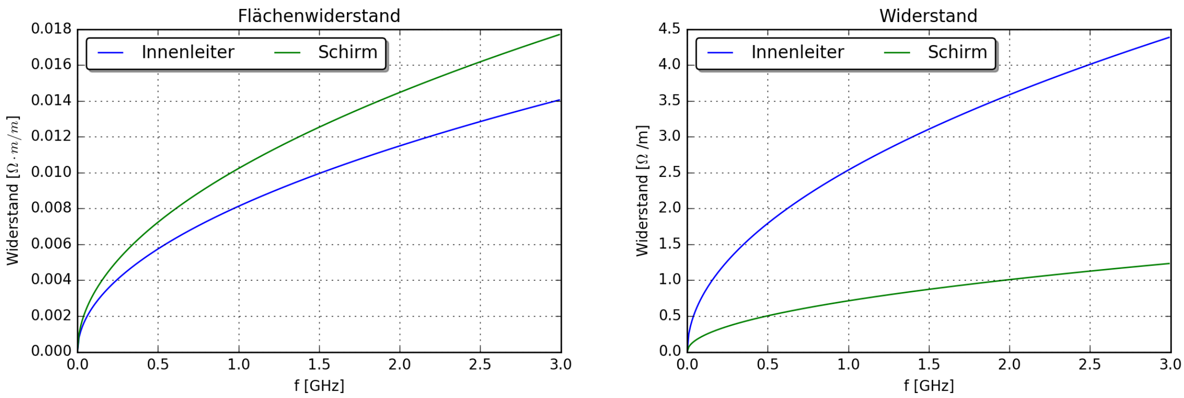
$$R_i = \frac{R_{Si}}{\pi \cdot d} \tag{11}$$

$$R_o = \frac{R_{So}}{\pi \cdot D} \tag{12}$$

Dividing the resistance by twice the line-impedance yields the attenuation – however in units of Neper which refer to the basis e. To obtain the attenuation in dB it is multiplied by the factor 20/ln(10).

$$\alpha_R = \frac{R}{2 \cdot Z_L} \left[\frac{Np}{m}\right] \tag{13}$$

IIn Fig. (4) the sheet resistance and the resulting resistance are given for a coaxial line with aluminium shielding (o = 3,77 • 107 S/m) and a copper inner conductor (i = 5,98 • 107 S/m). Although the conductance of aluminium is significantly lower, the inner conductor contributes most to the losses, because in it a significantly smaller area is available for the current.



(a) Sheet resistance (b) Resistance

Fig. 4: Sheet resistance and resistance

$$\alpha_R = \frac{20}{ln(10)} \cdot \frac{\sqrt{\pi \cdot f \cdot \epsilon_0 \cdot \epsilon_r}}{ln(\frac{D}{d})} \cdot \left(\frac{1}{d \cdot \sqrt{\sigma_i}} + \frac{1}{D \cdot \sqrt{\sigma_o}}\right)\left[\frac{dB}{m}\right] \tag{14}$$

In equation (14) the attenuation of the shield and the inner conductor are summarized. It is easy to see that the attenuation is proportional to the square root of the frequency. Moreover it needs to be remarked that the attenuation approaches 0 as the frequency decreases. The penetration depth approaches infinity and does not consider the finite diameter of the inner conductor and the finite thickness of the shield S.

In order to consider this, first the effective area for the shield and the inner conductor is calculated. In other words, the penetration depth of the current is considered for the finite diameter of the inner conductor and the finite thickness of the shield.

$$A_i = 2 \cdot \pi \cdot \zeta_i \cdot [r + \zeta_i \cdot (e^{\frac{-r}{\zeta_i}} - 1)] \tag{15}$$

$$A_o = 2 \cdot \pi \cdot \zeta_o \cdot [R + \zeta_o - (S + \zeta_o) \cdot (e^{\frac{\zeta_o - R}{\zeta_o}} - 1)] \tag{16}$$

Given the penetration depth:

$$\zeta = \frac{1}{\sqrt{\pi \cdot f \cdot \mu_0 \cdot \sigma}} \tag{17}$$

Substituting it in the equation for the dampening we get:

$$a_R = \frac{\sqrt{\pi \cdot f \cdot \epsilon_r \cdot \epsilon_0}}{2 \cdot \ln\left(\frac{R}{r}\right)} \cdot \left[\frac{1}{\left(r + \zeta_i \cdot e^{\frac{-r}{\zeta_i}}\right) \cdot \sqrt{\sigma_i}} + \frac{1}{\left(\zeta_o + R - (\zeta_o + S) \cdot e^{\frac{\zeta_o - R}{\zeta_o}}\right) \cdot \sqrt{\sigma_o}}\right] \tag{18}$$

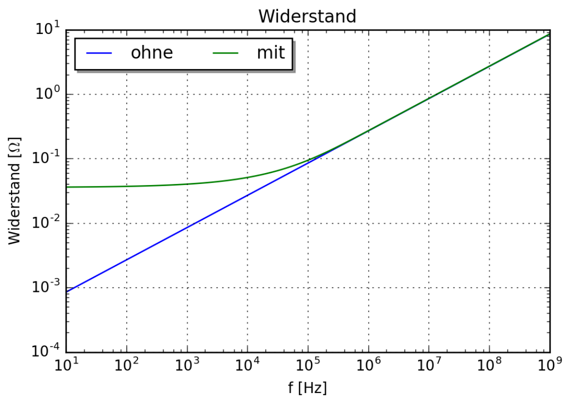


Fig. 5: Resistance with and without consideration of the DC-share

As can be seen from Fig. (5), the resistance now approaches a finite value as the frequency drops, instead of approaching zero.

For many coaxial cables the inner conductor and the shield are metalized. This may be a tinning – in order to make the easily solderable – or a layer of copper or silver. Since the penetration depth depends on the conductance, and since the current decreases according to an exponential function, a simple estimation is not possible anymore. The current in the first layer decreasing according to the exponential function becomes the starting value for the next distribution in the following metallization. This process is repeated for any further layers. Fig. (6) symbolically depicts it for a section of the inner conductor.

The effective conductance for n metal layers is calculated with equation (21).

$$\zeta(i) = \frac{1}{\sqrt{\pi \cdot f \cdot \mu_0 \cdot \sigma(i)}} \tag{19}$$

$$B(1) = 0 \qquad B(i+1) = \frac{t(i)}{\zeta(i)} \tag{20}$$

$$G_{tot} = 2 \cdot \pi \cdot \sum_{i=1}^{n} \zeta(i) \cdot \sigma(i) \cdot \left(e^{-B(i)} - e^{-B(i+1)}\right) \tag{21}$$

The attenuation results in:

$$a_R = \frac{20}{ln(10)} \cdot \frac{1}{G_{tot} \cdot 2 \cdot Z_L} \left[\frac{dB}{m}\right] \tag{22}$$

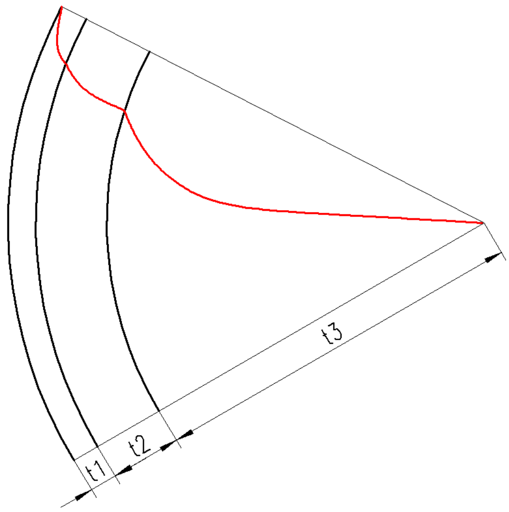


Fig. 6: Varied current distribution in the metalized wire

To see which influence the metallization has we look at two variants: first at a pre-tinned copper wire and second at a copper-plated solder wire (Fig. 7) As a comparison, a copper wire and a solder wire are also shown. It is easy to see that the resistance of the copper-plated solder goes down and approaches the value of copper as the frequency rises. Conversely, the resistance of the pre-tinned copper wire rises, and consequently so do the losses.

As a consequence we get: the diameter of the inner conductor is most relevant for the ohmic losses, as is the conductance at its surface.

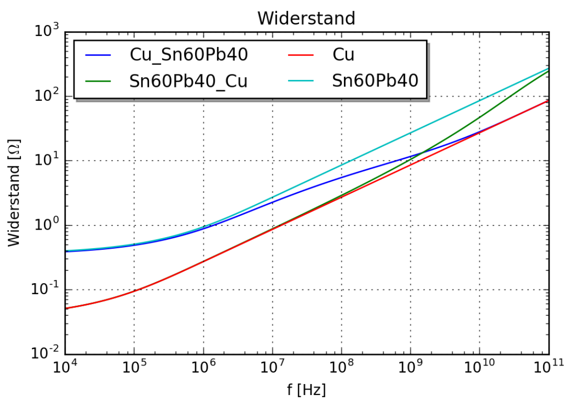


Fig. 7: Resistance of metalized conductors

For some lines, the inner conductor is made of stranded wires, or the shield of a braided mesh. With increasing frequency, the inevitable finish-roughness of the inner-conductor wire and of the foil-shielding also has an influence. Hammerstad and Jensen [5] published an empirical equation to consider this influence; however, this is only applicable up to about 15 GHz, and for small roughness values. For larger values it saturates or becomes inexact

.

$$K_w = 1 + \left(e^{\left(-\frac{\zeta}{2 \cdot R_a}\right)}\right)^{1.6} \tag{23}$$

$$R' = R \cdot K_w^2 \tag{24}$$

Gold and Helmreich [6] have published an approach based on physics which shows very good agreement. Unfortunately, there is no closed solution since part of it can only be solved numerically.

2.2 Dielectric attenuation

The dielectric losses may be imagined as conductance between the two conductors.

$$Y = \frac{4 \cdot \pi^2 \cdot f \cdot \epsilon_0 \cdot \epsilon_r(f)}{\ln(\frac{D}{d})} \tag{25}$$

$$G = Y \cdot \tan(\delta(f)) \tag{26}$$

Staring from this approach we get equation (27). One should not ignore that both the losses and the permittivity usually are dependent on frequency

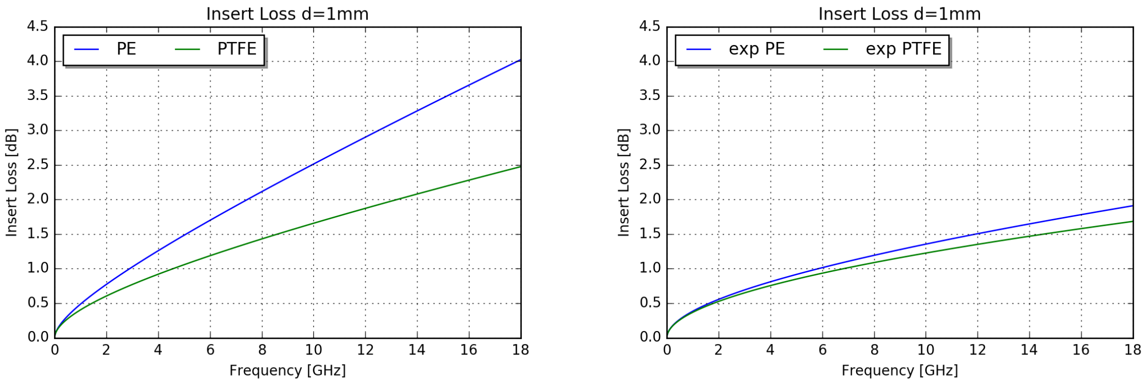
.

$$\alpha_D = \frac{20}{ln(10)} \cdot \frac{\pi \cdot f \cdot \tan(\delta(f)) \cdot \sqrt{\epsilon_r(f)}}{c_0} \left[\frac{dB}{m}\right] \tag{27}$$

The attenuation caused by the dielectric losses is proportional to the frequency. The influence can be minimised by reducing the share of the dielectric. This can be achieved for example by supports located at periodic distances for maintaining the position of the inner conductor in the middle, or by introducing a helix.

Another possibility is to enlarge the share of air within the dielectric. Polyethylene (PE) and polytetrafluoroethylene (PTFE) are well-established materials. PE can be foamed which does not work with PTFE.

For this reason, Robert Gore developed a process in 1969 where PTFE is heated to 300° C and then expanded abruptly, causing PTFE to constitute a fine mesh with bulges at the crossing points. The share of air is considerably increased; permittivity and losses drop. Fig. (8) shows a comparison between coaxial cables featuring PE, PTFE, expanded PE, and expanded PTFE; the diameter of the inner conductor is 1 mm. The shield diameter was correspondingly adapted to achieve an impedance of 50 Ω.



(a) Solid PE and PTFE

(b) Expanded PE and PTFE

Fig. 8: Losses using a solid and an expanded dielectric

2.3 Summary: attenuation

In the following, the individual contributions to the attenuation are listed once more, for the simple case of a coaxial line the shield and inner conductor of which are formed only from one metal, and which is filled with a dielectric:

$$\alpha_{Ri} = \frac{20}{ln(10)} \cdot \frac{\sqrt{\pi \cdot f \cdot \epsilon_0 \cdot \epsilon_r}}{ln(\frac{D}{d})} \cdot \frac{1}{d \cdot \sqrt{\sigma_i}} \left[\frac{dB}{m}\right] \tag{28}$$

Contribution of the shield:

$$\alpha_{Ro} = \frac{20}{ln(10)} \cdot \frac{\sqrt{\pi \cdot f \cdot \epsilon_0 \cdot \epsilon_r}}{ln(\frac{D}{d})} \cdot \frac{1}{D \cdot \sqrt{\sigma_i}} \left[\frac{dB}{m}\right] \tag{29}$$

Contribution caused by the losses in the dielectric:

$$\alpha_D = \frac{20}{ln(10)} \cdot \frac{\pi \cdot f \cdot \tan(\delta(f)) \cdot \sqrt{\epsilon_r(f)}}{c_0} \left[\frac{dB}{m}\right] \tag{30}$$

It is easy to see (Fig. 9) that in the depicted frequency range the losses caused by the inner conductor represent the dominant contribution. The dielectric losses mount proportionally with frequency and will form the largest contribution to the attenuation at higher frequencies.

For most coaxial cables the dimensions are not specified. As a consequence, the attenuation cannot be calculated. For some cables, the manufacturers provide specific parameters. These include all frequency-independent elements and are referenced either for frequencies in GHz or (more rarely) for frequencies in MHz.

$$IL = l \cdot (K1 \cdot \sqrt{f} + K2 \cdot f) \tag{31}$$

IL : Attenuation [dB]
f : Frequency [GHz]
K : Resistive attenuation factor
K2 : Dielectric attenuation factor

In K1 and K2 all frequency-independent contributions are summarized i.e. it is assumed that tan(δ) and ε are constant, as well.

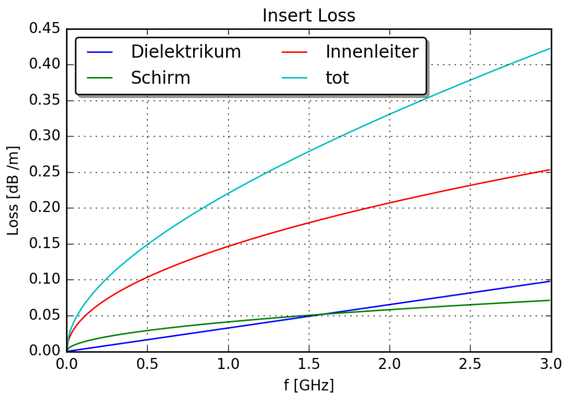


Fig. 9: Individual contributions and overall attenuation

3 Phase-stability

For many applications it is important that the phase remains stable during operations. For example, when calibrating a network analyzer, the complex amplitude is measured in order to calculate correction values from it. If the phase changes during operation, the correction values do not fit anymore and the measured results will be represented more or less incorrectly.

3.1 Phasen-stability dependent on temperature

As materials are getting warmer they also expand (safe for a few exeptions). As a result, the coaxial line grows longer with increasing temperature, and shorter with decreasing temperature.

$$l(T) = l_0 \cdot (1 + T_K \cdot \Delta T) \tag{32}$$

Here, l_0 stands for the length of the line at reference temperature, TK for the expansion coefficient, and T for the temperature difference.

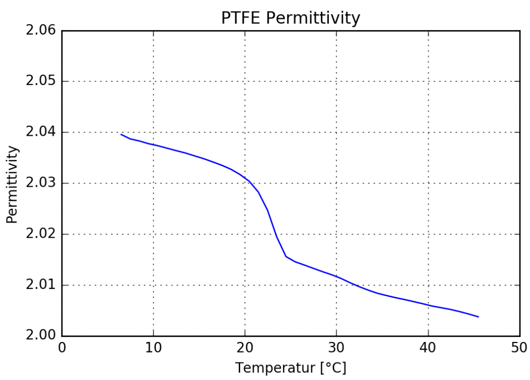
The data sheet usually includes the relative phase change in [ppm]. It is calculated as follows:

$$\Phi = \frac{l}{\lambda} \cdot \sqrt{\epsilon_r} \cdot 360^\circ \tag{33}$$

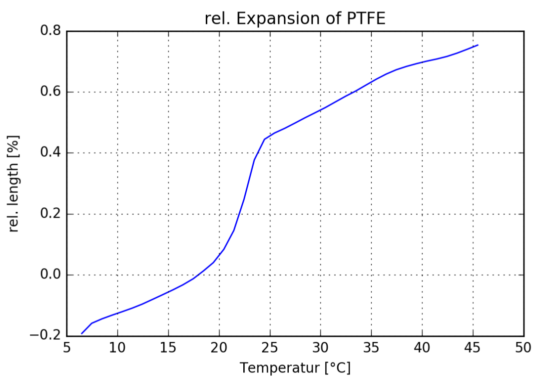
$$\Delta\Phi = \frac{\Delta\varphi}{\Phi} \cdot 10^6 \, [ppm] \tag{34}$$

For a coaxial line made of copper with air as the dielectric $(T_K = 16.5e^{-6}\frac{1}{K})$ we get a phase change of ±1000 ppm for the temperature range from -40°C to +80°C.

The permittivity of the dielectric depends on the type of molecules. As the dielectric expands, fewer molecules are contained in the same volume and the permittivity decreases. In the ideal case, the expansion of the line and the decrease of the permittivity compensate each other.



(a) Permittivity



(b) Rel. expansion

Fig. 10: PTFE Parameter

The phase change can be minimised by accordingly adapting the share of the air in expanded PTFE. In a cable correspondingly optimized, the relative phase change drops to ±300 ppm (Fig. 11). Further information on the properties of PTFE may be found in [7] [8].

3.2 Phase changes due to bending

As a cable is being bent, generally the dimensions of the cable change, as well. The round shield may take on an oval shape, the inner conductor may migrate away from the centre, the dielectric will be compressed, and the electric properties of the shield change. This in combination results in a different propagation velocity that makes itself felt as a phase change.

Testing of cables involves bending using a defined diameter. There is no uniform standard, and consequently various test procedures are applied. This makes it difficult to compare. Some bend the cable by 360° around diameter D1; others use ±90° around the diameter D2. Others again wait a certain amount of time until they determine the result. When in doubt it will be best to let the cables in question undergo ones own tests.

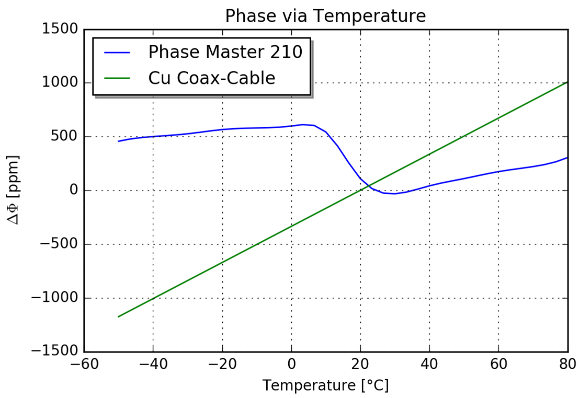


Fig. 11: Phase change of a copper cable and an opt. PTFE-cable

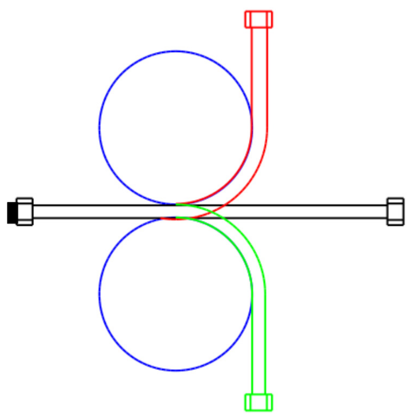


Fig. 12: A variant for a bending-device

4 Further influencing variables

In [10] the question is discussed whether the ambient air humidity influences the electrical characteristics of a cable. Calculations and measurements showed that a change of the humidity by ±50 % changes the travel time by ±40 fs ändert. In normal applications this may be disregarded.

Ionizing radiation more or less quickly changes material characteristics. If it is strong enough it will destroy the materials. In [9] the influence of ionizing radiation on two different low-density PTFE cables was investigated. Significant differences were shown. Both cables showed an increase in insertion loss, however in one cable this value was 7 times as big as in the other cable.

5 Protection and handling

5.1 Kink-protection

As can be seen from the explanations above, the cable should not be bent more strongly than using a specified minimum radius. During regular handling, the cable acts as a soft lever and exerts the largest force at the cable/connector junction. To avoid kinking of the cable, a suitably designed kink-protection should be attached. It has the function to spread out the occurring forces along the cable.

At the connector it should be stiffer and become steadily softer towards the cable. With this, the cable will follow a more or less uniform curve.

In practice, a 3-fold-staggered shrink-on tube has proven itself. The sections are layered on top of each other from the shortest to the longest, as shown in Fig. (13).

There are also coaxial lines that may be kinked without any impact on the electrical properties. The Storm Flex® by Teledyne Storm Microwave may be bent directly at the connector. By using it angled plugs become unnecessary – they have mostly worse characteristics than straight plugs, anyway.

Fig. 13.Staggered shrink-on tube as kink-prevention

5.2 Protection of the cable

If during operations there is a risk of stepping on the cable, running over it with a car, or subjecting it to strong abrasion, armouring should absolutely be provided. For example:

- **Nylon fabric**

Especially in the case of abrasion, a coaxial cable is protected efficiently against damage by a nylon tube.

- **Plastic helix**

Some manufacturers offer a plastic helix covered by a FEP tube as additional protection. This is adequate if the cable is stepped on accidentally or becomes jammed e.g. between two trolleys carrying the measuring equipment. The arrangement is however not suited for protection against stronger stress or constant stepping onto the cable.

- **Steel helix**

Considerably stronger protection is offered by a steel helix with FEP cover. Generally, the maximum pressure which a cable correspondingly protected can bear will be provided. This should leave the cable well protected if it is on the floor and stepped upon.

- **Articulated hose**

The articulated hose (hard armour) looks like a shower hose made of stainless steel and can protect the cable even as a car runs over it. Moreover, this heavy amour guarantees a minimum bend radius due to its construction, this being a positive side effect.

Fig. 14: Coaxial cable sheathed by an articulated hose

5.3 Connectors

Coaxial cables used for measurements carry a plug on each end. Almost all of such plugs have a screw-on connection – in contrast the BNC plug has a bayonet lock. A part of the plug has a moving section fixing it to the socket. Caution: the term "plug" implies that the part is inserted into the socket, and not that it is turned while connecting it. The bellows in the plug is not designed such that the pin may be subjected to a rotary motion. If this happens nevertheless, it will scrape along the surface and the characteristics of the plug will deteriorate. It is only the movable nut that may be rotated.

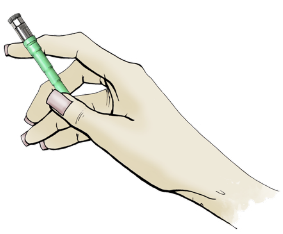
Also highly popular is turning calibration standards, adapters or attenuators since they sit so comfortably in our hand. Calibration standards are highly sensitive and rather expensive. They in particular must not be subjected to wrong handling.

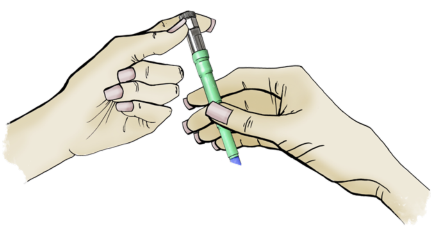
To obtain a secure and reproducible connection, the plugs should be tightened using the torque specified by the manufacturer. If the torque is too weak – as it may be when only manually fastening the plug – any very small vibration can deteriorate the connection. If, on the other hand, the plug is fastened too tightly, it (or the socket) may be damaged to the extent that one or even both need to be changed. If this happens with the socket of a instrumentation device or signal generator, the unit needs to be shipped to the manufacturer, and it will be back only after 2 or 3 weeks, accompanied by a hefty bill.

My recommendation is to acquire a matching torque wrench for each type of plug, and to use it always. This results in a significantly higher reliability and will be much less expensive.

In addition, the number of plugging cycles should be monitored. The manufacturer should specify for each plug how often it may be plugged without losses in its characteristics.

There are various qualities. In particular the low-cost connectors with the gleaming cold contacts have no protection against wear. After only a few plugging cycles the soft gold layer has worn off and contaminates the plug. High-quality plugs have a housing and a union nut of stainless steel because only this material has the required firmness to deal with tough requirements. More information on the various plug types are here [11].





The elspec HandFlex. A semi rigid cable bendable by hand. Matchable in multiple ways and thus highly economic.

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