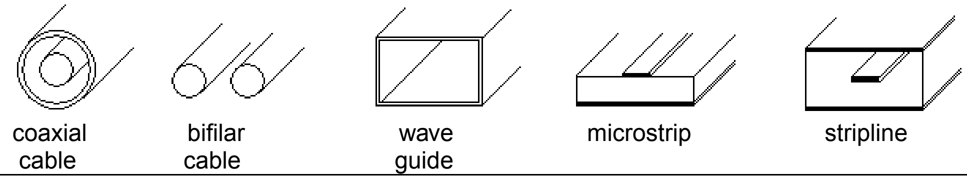
Here follows some informations useful to understand the basic concepts about coaxial cables, with the tricks of the trade and curious informations that are rare to find on school books and manufacturers catalogs.

Introduction to coaxial cables

Perhaps none of us have never thought that the development of radio communications would never have been possible without the invention of coaxial cable, it is continuously used in our applications that we don't think about that. The attribution of the invention of coaxial cable is complex and contrasted, there are several American and European patents already near the end of '800 (the first patent is in 1880 by O. Heaviside UK) the discovery is then fell into obscurity for many years because surely there was nothing to make pass in a coaxial cable !!
The real discovery and its actual use dates back to 1929 due to the need for a more efficient and with less interferences conductor for the transmissions of many telephone channels on a single "carrier".
In the early 30s, this technique was also advantageously used for the first experiments with the emerging television and so on until today. The drawing below shows all the transmission lines used in RF, from KHz to GHz, the coaxial cable line is the most used and most cost-effective, it can be used by up to 110 GHz with the current technology.



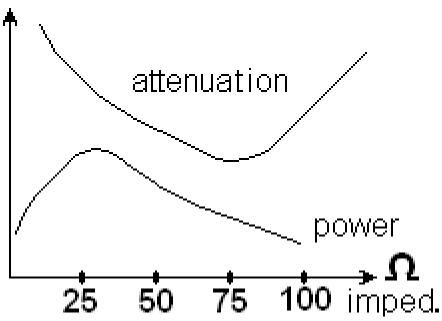
transmission lines used for RF

To better understand the characteristics of a coaxial cable it is also necessary to know all the parameters associated with it, for reasons of space we will cover just some of the most important that are:

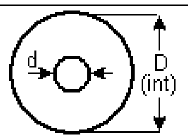
Impedance - Attenuation - Cut-off frequency and optimal frequency
Max handling power - Return Loss - Propagation velocity

IMPEDANCE

The impedance of a coaxial line (over about 1 MHz) depends only on the type of dielectric used, or by the dielectric constant εr, and the ratio between the diameter of the inner conductor and the inner diameter of the outer screen (not the size) and it is independent of the length and frequency. But why are there 50Ω and 75Ω cables?
From the graph at side we can see clearly that the lowest attenuation is achieved at about 75-77Ω of impedance and the maximum power handling at around 30Ω (with cables of same size).
The U.S. Navy during World War II decided to take the value of 52Ω as a compromise between attenuation and maximum power (then rounded to 50 Ω). With the birth of television, it was decided instead to adopt the value of 75 Ω because it ensured the minimum attenuation, because in air TV reception there is no power along the cables. Given the primordial TV receivers systems, VHF at fist an than UHF, and the high attenuation, it was definitely the right choice.



Ratio between the diameter of the inner and outer conductor for the impedance of 50 and 75 Ω with various dielectrics



impedance	Air εr 1	Polyethylene εr 2,3	Teflon εr 2,04	Foam εr ~ 1,5
50 Ω	2,3	3,5	3.3	2,8
75 Ω	3,5	6,6	6	4,6

The standardization to 50Ω was a decisive step because already in Europe in the early post war, Germany took the value of 60Ω thinking it was the right choice because it is a half way between 50 and 75Ω. The standardization to 50Ω was very important, as at each side of the cable it has to plug something, or rather a lot of "things" that have to be standardized to 50Ω too.
In addition to the 50 and 75Ω cables there are also some strange and particular values, let's see what they are:
- 12.5 and 25 Ω cables: for transformer and matching of power stages, eg. FET push-pull and / or broadband.
- 35 Ω cables: for the production of hybrid couplers, it is used also to match impedance at λ / 4 between 50Ω and 25Ω (25Ω is the result of two 50Ω in parallel).
- 70 Ω cables: to build Wilkinson combiners.

These cables are usually available in rigid or handy-form semi-rigid configuration in order to obtain the best performance being used in particularly critical or high power stages.

Formula for calculating the impedance

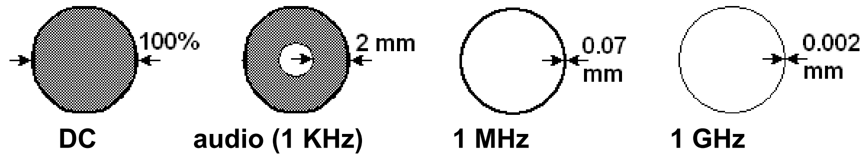
$$Z = \frac{138}{\sqrt{\varepsilon r}} \times \log \frac{D}{d}$$

ATTENUATION

The attenuation, after the impedance, is the most important discriminating in the choice of a coaxial cable, it is linearly proportional to the length of the cable in fact it is measured in dB / meter. The attenuation depends on the goodness of dielectric, on the physical size and on the skin effect of the conductors, so it is intuitive that the lowest attenuation occurs with large cables and with air dielectric. The air dielectric is very complicated to implement and it is generally used only for TV or radio broadcast where the power is impressive, moreover these cables require vacuum pumps to prevent contamination by external agents of the air dielectric (moisture and condensation). A very cheap way to reduce loss consists of injecting an inert gas (nitrogen) in the dielectric to obtain a dielectric constant as close as air, this is often done with foam cables but also with teflon ones.

The addition of gas contribute also for a more long-term stability of the cable parameters even under critical conditions like moisture and temperature changes. The choice of dielectric is important to have less losses in the cable, in fact with teflon dielectric the insertion loss is less than with the classic polyethylene, but the true breakthrough in terms of attenuation is achieved only with expanded dielectric, whether it is foam or teflon.

The attenuation for skin effect of the conductor is equal to the square root of frequency and with a silver plated conductor it is slightly improved the attenuation. As a general rule skin effect loss dominates from low to mid frequencies and dielectric loss dominates at high frequencies. The propagation characteristics of surface due to skin effect is used in some cables as an economic advantage because it is possible to use poorer or cheaper conductor, with coatings such as copper or silver, that’s because low attenuation cables have a tubolar copper or solid copper plated aluminium internal conductor.



skin effect at different frequencies

SKIN EFFECT
by rising in frequency the resistance of the cable increases because the current flows only on the outer part (the outer conductor) and only on the inside (regarding the shield)

Obviously, increasing the size of the coaxial cable there is less attenuation up to the cut-off frequency. The outer shield too increase the attenuation but its contribution is always smaller than the other two factors. In fact, a little-known aspect to consider is the layer of outer conductor that acts as a shield, if this is too small there is greater attenuation caused by the loss of signal due to radiation, that is for a not good shielding of the cable (see RG 58). A small contribution to the increase of losses is also due to using an inner conductor composed of many wires, if this technique improves the flexibility of the cable, however, it introduces a very small increase in losses of around 5%.

CUT-OFF FREQUENCY - MAX OPTIMAL FREQUENCY

The cut-off frequency of a coaxial cable is not to be confused with the maximum frequency where it is "convenient" to use a particular cable. A given cable makes sense to be used up to a certain frequency (sometimes recommended by the manufacturer and referred as "operating frequency") simply because up to that frequency parameters are quite suitable for its use, at same frequency the same cable can’t be used for different applications. For example in microwave radio links wirings, even at 20 GHz, are used handy-form cables 10 to 30 cm long for internal interconnections, it will not be possible to use the same cable for antenna connection, 10 or 20 m at the same frequency, since for such long distances the attenuation would be too high, these cables are not suitable for outdoor use. When choosing a cable is often not considered the factor of insulation that depends on the shielding of the outer conductor, for example in a wiring inside of a VHF or UHF radio link is not acceptable to use a single shield cable, with the risk of RF coupling between Tx and Rx undermining the goodness of a good duplexer filter with 80 dB of insulation between Tx and Rx, in fact, the coupling between two RG58 cables that pass parallel for 3 or 4 cm have an insulation of only 70-75 dB. So in the choice of a cable must be considered about ten different factors, many of which are in conflict with each other.

The cut-off frequency represents instead the maximum absolute frequency of use, and over of that there are various resonances that change the phase and amplitude in the propagation of electromagnetic waves in the cable itself.

The propagation in a coaxial cable is defined as TEM (Transversal Electric and Magnetic Field), the electric and magnetic field lines are perpendicular to the cable. Beyond the cut-off frequency strange resonances appear in the propagation and they produce phenomena not easily foreseeable. The cut-off frequency is inversely proportional to the size of the cable, it is actually a much higher value of the maximum optimal frequency except for the semi-rigid cables since due to their design and very good quality they can be used up to their cut-off frequency. For very high frequencies it is better to use small diameter cables considering also the attenuation.

Max cut-off frequency and max optimal frequency suggested for some coaxial cables

Type	RG 58	RG 223 (double shield)	RG 213	RG 214 (double shield	RG 316	RG 316 (double shield)	RG 142 (double shield)	UT 141 Multiflex 141	UT 086 Multiflex 86
cut-off freq.	~ 20 GHz	~ 20 GHz	~ 12 GHz	~ 12 GHz	~ 30 GHz	~ 30 GHz	~ 20 GHz	33 GHz	40 GHz
max optimal freq	100-1000 MHz	3 - 6 GHz	2 - 4 GHz	4 - 8 GHz	2 - 3 GHz	3 - 6 GHz	4 - 8 GHz	26 GHz	33 GHz
	Ø 5 mm		Ø 10 mm		Ø 2,5 - 3 mm		Ø 5 mm	Ø 4 mm	Ø 3 mm
	polyethylene insulation				**teflon insulation**				

NOTE for the RG-58 cable the scarce shielding and the poor quality are factors that highly decrease the performances.

MAX HANDLING POWER

For very high power applications, as mentioned above, are used cables with air dielectric, the central conductor is held in the center by a sort of coil that runs along the length of the cable. For medium-high power applications are used cables with teflon dielectric, which can work up to 165 °C, at the same size Teflon insulation allows to handle up to the triple of maximum power than polyethylene cable. Increasing frequency the maximum handling power decreases, both due to dielectric and skin effect losses moreover losses increase a lot the temperature of the cable. For even higher temperature applications it is available a special cable with fiberglass jacket (RG115) that can work up to 200 °C with a diameter of only 10.4 mm, it can hold up to 6 KW at 100 MHz and the same jacket allows the installation near heat sources.

RETURN LOSS

The return loss of a coaxial cable, ie the impedance matching, is almost never considered in the selection, because manufacturers rarely provide this information. In fact when you assemble a coaxial cable with a connector is then very difficult to understand if the impedance matching depends on the cable, on the connector or on the quality of the assemby. However we can give an advice due to our experiences of thousands of tests made on coaxial cables, we can say that all double shield coaxial cables behave, in terms of return loss, much better than similar single shield cables (RG223 against RG58, RG214 against RG213, 2 shields RG316 against RG316, etc.. see table above). For example, using the same SMA connector and the same care in assenbling, the double shields RG316 can be used beyond 6 GHz with a typical return loss of 20 dB, while a standard RG316 cable would give similar return loss results at about 2-3 GHz. Remember that a good impedance matching is not only important to have low loss but also to avoid altering the device impedance of a connected device. For example, if you connect a good bandpass filter, well calibrated by a network analyzer, to a mismatched cable you will get an increase of ripple in the filter and other not forseeable effects depending on the mismatch and the phase. To make an example we can say that a cable for wiring and general use is considered good with a return loss value up to 20dB, at microwave frequencies up to 16dB, for lab or testing cables there are differnt values (see below).

PROPAGATION VELOCITY - εr - DIELECTRIC CONSTANT

Depending on the dielectric and so on its εr, the propagation velocity of a cable decreases according to a number that indicates the percentage of speed compared to air, such as in common polyethylene cables (RG 58, 213, etc.) the speed factor is equal to 66%, in this cable the wavelength is shortened by 34% compared to air. The speed factor is used to calculate impedance matching stub or the real wavelength in the cable. For example a cable λ/4 long, as impedance adapter, at a frequency of 100 MHz, the length for a cable type RG 213 can be calculated as follow:

λ_{AIR} at 100 MHz = 300 : 100 = 3m -> $\lambda/4_{AIR}$ = 3m : 4 = 75cm -> for RG 213 V=66% $\lambda/4_{CABLE}$ = 75 x 0,66 = 49,5cm

The εr value, as seen above, is one of the two factors that determines the characteristic impedance of the cable, in general terms the more it is high (and therefore is near to air), the less is the attenuation.

TEST AND LAB CABLES

Regarding the laboratory and testing cables of course are valid all the considerations made so far although other factors can be involved in the selection, in our opinion low return loss and phase-amplitude stability vs. flexure are very important factors, that's why the test cables are so expensive and difficult to assemble. These high quality cables are made with low density teflon dielectric (microporous cables) in order to obtain a low loss and high flexibility, they have a double or triple shield and special machines are used to assemble them, they are then subjected to thermal cycles to highlight imperfections or other defects. In these laboratory cables is very important to over strengthen the connection between the connector and cable to increase last in time, in fact, if it is difficult to break a cable along its length it is much easier that this happen at the point of transition from the connector to the cable.

With Multiflex141 cables by Suhner it is possible to achive a fair compromise between performances and price, even if we asseble them by ourselves with SMA connectors it is easy to obtain a good result up to 15/18 GHz, with the exception of phase stability vs. flexure that is a prerogative only of much more expensive cables made by famous brands. As an indication a good test cable must have a maximum return loss of 25 dB which can reach 22-20 dB at microwave frequencies but only at the limit of its maximum frequency of use, a so low value of return loss is required to obtain very reliable measures. The goodness of a test cable is easily verified by taking several bends on the cable connected to a network analyzer, the variations in amplitude and phase must be very small.

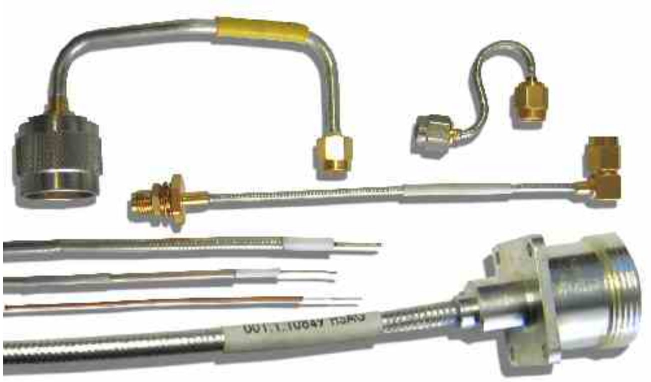
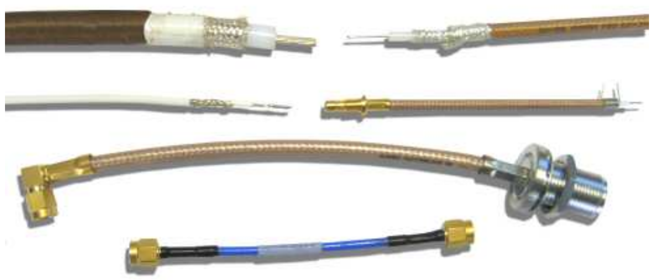
Often in the code of a coaxial cable there is a prefix unknown to many people, RG stands for Radio Guide, the US Military specifications provide the coaxial cables standardization, although no longer in use it is still a standard to describe many coaxial cables and still widely adopted. Now there is the Mil-C17, substituted by Mil-DTL-17.

COAXIAL CABLES , for RF - μWAVE - VARIOUS

For our convenience and for obvious technical reasons, we divided coaxial cables in five categories:

-- A) rigid, semirigid, hand-formable coaxial cables, eg. UT 085 , SM141 , Multiflex etc...
-- B) flexible coaxial cables with teflon dielectric, eg. RG 316 , RG 142 , RG 179 etc...
-- C) flexible coaxial cables with polyetylene dielectric, eg. RG58 etc...
-- D) coaxial cables with foam dielectric, eg. Cellflex series, RT5020 etc...
-- E) super-flexible coaxial cables for laboratory purposes, eg. Sucoflex series etc...

Each of these categories has its own advantages and limitations which are the basis of choice for a particular purpose. On the catalogue they are further divided into not assembled cables (sold by meter) or already assembled.
For our choice of business but also for our attitude will be particularly present in the catalog, with great choice, all types of cables with teflon dielectric.

some examples	particularities and applications
	**A) rigid, semirigid, hand-formable coaxial cables** -- large impedance selection: 12.5, 25, 35, 50, 70 and 75Ω -- low loss and very good impedance precision typ. ± 1 Ω low return loss even at microwave frequencies -- good repeatability, aging and phase stability -- typical temperature range -40 / + 160 °C -- high shielding level -- available also an anti-magnetic version -- very good for internal RF and microwave wirings -- they are not suitable for laboratory usage except for flexible Multiflex 086 or 141 -- for the same diameter can be used the same connector type for rigid, semirigid and hand-formable types
	**B) flexible teflon cables** -- low loss and good impedance precision typ. ± 2 Ω up to 3 GHz , they can be used up to 6 GHz -- typical temperature range -40 / + 160 °C and up to 200 °C only for RG 115 type -- good repeatability, aging and phase stability -- good flexibility up to 5mm diameter -- good for laboratory usage up to 3 GHz -- not damaged by moisture, UV, etc... -- they can handle medium and high power
	**C) flexible polyethylene cables** -- specifications are very good if compared with the low price, they are widely used in HF - VHF and video -- good shielding for double shield models min. 80 dB up to 6 GHz for RG 223 and 214 while for single shield models min. 40 dB up to 2 GHz for RG 58 and 213 -- for laboratory usage up to 1 GHz
	**D) foam cables** -- they are the cables with the lowest loss but also with less flexibility and not suitable for lab or professional usage -- if braid shielded they are quite flexible -- corrugated types are suitable only for antenna connection with very low insertion loss -- usable up to 3 GHz , max 6 GHz
	**E) super-flexible micro-porous teflon cables** -- they are definitely the most efficient and sophisticated among all cables but also the most expensive, they are used exclusively in labs even up to 100 GHz -- excellent stability over time, the phase remains constant even if handled continuously -- very low loss and very good return loss -- they are used also for flexible wirings on over 10 GHz radio links

Microwave coaxial cables are available in many different types but their only true difference is the external conductor that causes the possibility or not to be hand-formable , while electrical performances are quite the same at the same diameter , less attenuation is possible by increasing the diameter . All cables in these pages are teflon insulated .
TIP : the number in the code UT047 , UT086 , UT141 etc. indicates the measure of diameter expressed in mils of inch .

Microwave cables
rigid, semi-rigid, hand-formable, flexible

normal semirigid

external natural copper
or tin plated
or silver plated,
they are the traditional semirigid cables for microwave frequencies

25 - 50 - 70 - 75 Ω

hand-formable

external tin plated copper braid for outer conductor gives to the cables a good hand-formability

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aluminium hand-formable

external aluminium is little more rigid than the normal hand-formable but more resistant,
the weight is 30% less

12.5 - 25 - 35 - 50 - 70 - 75 Ω

non magnetic

it is a special version of hand-formable types for special medical applications and RF applications at low intermodulation like digital transmission or GSM , DECT etc...

50 Ω

flexible Multiflex 086 - 141

they are similar to the normal flexible coaxial cables but for applications over 18GHz too, the same connectors for the semirigid can be used with Multiflex cables

50 Ω