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Connectors, Air Lines and RF Impedance

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Abstract

This lecture will give information on impedance considerations for measurements at RF and microwave frequencies. The subject matter is divided into three areas:

- Coaxial connectors used to perform precision transmission line measurements
- Air lines used to define characteristic impedance in coaxial line
- Special considerations needed when defining impedance and using impedance concepts at RF

About the Speaker

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Connectors, Air Lines and RF Impedance

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LIST OF SYMBOLS USED IN THESE NOTES

a = radius of coaxial line centre conductor (m).
α = attenuation constant ($Np.m^{-1}$).
b = radius of coaxial line outer conductor (m).
β = phase constant ($rad.m^{-1}$).
γ = propagation constant for coaxial line containing conductor loss. This is generally a complex-valued quantity (m^{-1}).
γ_0 = propagation constant of lossless coaxial line. This is an imaginary-valued quantity (m^{-1}).
C = shunt capacitance, per unit length, of coaxial line including conductor loss ($F.m^{-1}$).
C_0 = shunt capacitance, per unit length, of lossless coaxial line ($F.m^{-1}$).
c = speed of light in vacuum (defined exactly as 299 792 458 $m.s^{-1}$).
δ_s = skin depth of air line conductors (m).
$\Delta\varphi$ = phase change (in degrees or radians) introduced by a length of line, l.
e = 2.718 281 828 ... (base of Naperian logarithms).
ε = permittivity, $\varepsilon = \varepsilon_0\varepsilon_r$ ($F.m^{-1}$).
ε_r = relative permittivity of an air line's dielectric (e.g. ε_r = 1.000649 for 'standard' air at 23°C, 50% relative humidity and 1013.25 hPa atmospheric pressure).
ε_0 = permittivity of free space (defined exactly as $(c^2\mu_0)^{-1}$ = 8.854 187 817 ... × 10^{-12} $F.m^{-1}$).
f = frequency (Hz).
f_c = cut-off frequency for the TEM mode (Hz).
G = shunt conductance, per unit length, for a coaxial line including conductor loss ($S.m^{-1}$).
j = $\sqrt{-1}$.
k = angular wave number, $k = 2\pi/\lambda$ ($rad.m^{-1}$).
l = length of air line (m).
L = series inductance, per unit length, for a coaxial line including conductor loss ($H.m^{-1}$).
L_0 = series inductance, per unit length, for a lossless coaxial line ($H.m^{-1}$).
λ = wavelength = v/f (m).
λ_c = cut-off wavelength for the TEM mode (m).
μ = permeability, $\mu = \mu_0\mu_r$ ($H.m^{-1}$).
μ_r = relative permeability of an air line's dielectric (e.g. μ_r = 1 for 'standard' air, to six decimal places).
μ_0 = permeability of free space (defined exactly as $4\pi \times 10^{-7}$ $H.m^{-1}$).
π = 3.141 592 653 ...
R = series resistance, per unit length, for a coaxial line including conductor loss ($\Omega.m^{-1}$).
σ = conductivity of an air line's conductors ($S.m^{-1}$).
v = speed of the electromagnetic wave in the air line ($v = c/\sqrt{\varepsilon_r}$ ($m.s^{-1}$)).
ω = angular frequency, $\omega = 2\pi f$ ($rad.s^{-1}$).
Z = characteristic impedance of a coaxial line containing conductor loss. This is generally a complex-valued quantity (Ω).
Z_0 = characteristic impedance of a coaxial line with lossless conductors. This is a real-valued quantity (Ω).

1 INTRODUCTION

These notes give information concerning some 'impedance' considerations that can be useful when making transmission line measurements at RF and microwave frequencies. The subject matter is divided into the following three areas:

i) connectors – the mechanisms used to join together two or more transmission lines;

ii) air lines – components used to define certain characteristics of transmission lines (such as impedance, phase change, etc);

iii) RF impedance – special considerations needed at lower microwave frequencies (typically, below 1 GHz) when defining the impedance of electrical components and networks.

The treatment of connectors deals only with coaxial connectors used to perform precision transmission line measurements (e.g. of power, attenuation, impedance and noise)[1]. Similarly, only air lines used to realise standards of impedance for these connector types are considered. For both connectors and air lines, only the 50 ohm variety is dealt with in any detail. Finally, consideration for the electromagnetic properties (such as characteristic impedance, propagation constant, etc) of these lines at lower microwave and radio frequencies (RF) is considered.

2 HISTORICAL PERSPECTIVE

The use of high frequency electromagnetic signals dates back to the late 19th century and the experiments of Hertz [1] validating the theory of electromagnetic radiation proposed by Maxwell [2]. For the majority of these experiments, Hertz chose to use guided

[1] Note: 7/16 connectors are not referred to explicitly in these notes. However, some information is given on this type of connector in the appendix towards the end of these notes.

electromagnetic waves, including a primitive form of coaxial line, and this essentially gave birth to the science of guided-wave RF and microwave measurements. However, a period of approximately 40 years passed before commercial needs for this new science began to emerge and new technologies (e.g. reliable signal sources, etc) became available.

2.1 Coaxial Connectors

During the 1940s, work began on developing coaxial connectors that were suitable for high frequency applications [3], and this led to the introduction of the Type-N connector, which is still used extensively today throughout the industry. Other connector types followed. Many of these connectors are still in use today (such as BNC, TNC and SMA connectors), however, many others have since become obsolete. By the late 1950s, a general awareness began to emerge concerning the need for precision coaxial connectors to enable accurate measurements of transmission line quantities to be made. To address this need, committees were established during the early 1960s (including an IEEE committee on precision coaxial connectors) and these produced standards [4] for the 14 mm and 7 mm precision connectors. These connectors were manufactured by General Radio and Amphenol, respectively, and hence became known colloquially as the GR900 and APC-7 connectors (GR900 being the 900 series General Radio connector, and APC-7 being the 7 mm Amphenol Precision Connector). Around the same time, a precision version of the Type-N connector was also introduced.

During the 1970s and 1980s, additional 'precision' connectors were introduced, generally of smaller size[2] to accommodate a wider frequency range of operation. These included the 3.5 mm [5]; 2.92 mm (or K-connector)[3] [7], 2.4 mm [8], and 1.85 mm (or V-connector) [9] connectors. In recent years, devices and measuring instruments have been manufactured fitted with 1 mm connectors [10]. Table 1 shows the approximate dates for the introduction of all these connectors (as well as, for reference, the BNC, TNC and SMA connectors, although these are not precision connectors).

[2] The "size" of a coaxial connector refers to the internal diameter of the outer conductor constituting the coaxial line section of the connector containing air as the dielectric.

[3] It is interesting to note that a version of the 2.92 mm connector was actually introduced back in 1974 [6], but this was not a commercial success. This was probably due to compatibility problems with other connector types existing at the time.

TABLE 1 - approximate dates at which some coaxial connectors were introduced

Decade of introduction	Connector
1940s	Type-N BNC
1950s	TNC SMA
1960s	7 mm (APC-7) 14 mm (GR900) Precision Type-N
1970s	3.5 mm
1980s	2.92 mm 2.4 mm 1.85 mm
1990s	1 mm

The precision connectors shown above are used nowadays in most laboratories involved in high precision RF and microwave measurements. This warrants a closer look at the properties of these connectors (as given in section 3, below).

2.2 Coaxial Air Lines

The use of precision coaxial lines as primary impedance standards also dates back to the early 1960s [11, 12]. These lines use air as the dielectric medium due to the simple, and predictable, electromagnetic properties (i.e. permeability and permittivity) of air at RF and microwave frequencies. The subsequent development of these lines has closely followed the development of the precision coaxial connectors, mentioned above, with smaller diameter line sizes being produced to interface with the various different types of connectors. Air lines are now commercially available in the 14 mm, 7 mm, 3.5 mm, 2.92 mm, 2.4 mm and 1.85 mm line sizes. It is only for the 1 mm line size that air lines are not presently available. This is presumably due to the difficulties involved in accurately machining such small diameter conductors (bearing in mind that in order to achieve a characteristic impedance of 50 ohms, the 1 mm line size would require a centre conductor with a diameter of less than 0.5 mm). The air lines currently used as impedance standards are discussed in section 4, below.

2.3 RF Impedance

Closely following the evolution of air lines as absolute impedance standards at microwave frequencies has been a consideration of the problems involved in utilising these, and similar, standards for impedance at RF[4]. However, the physical phenomena affecting the characteristics of these standards at these frequencies have been known about for many years. Indeed, the discovery of the so-called "skin effect", which affects the use of air lines as standards at these frequencies, was made by Maxwell and other eminent workers in this field during the late 19th century (e.g. Rayleigh [13]). Subsequent work during the early-to-mid 20th century established expressions for the series resistance and inductance of conductors due to the skin effect [14] and this led to formulas being developed [15, 16] for various forms of transmission line, including coaxial lines.

During the 1950s and 1960s, precision near-matched terminations were developed [17, 18] as alternative impedance standards, especially for use at lower microwave frequencies. Recent work has used a combination of air lines and terminations for RF impedance standardisation [19, 20]. Some of the considerations involved in RF impedance measurement and standardisation are given in section 5, below.

3 CONNECTORS

It is often the case that in many RF and microwave measurement applications, the role played by the connectors is overlooked. This is presumably because many connectors, particularly coaxial connectors, appear to be simple devices that are mechanically robust. In fact, the performance of any device, system or measuring instrument can only be as good as the connector used to form its output. A greater awareness of connector performance is therefore a great asset for individuals involved in RF and microwave applications involving connectors.

There are several useful documents giving detailed information on various aspects of coaxial connectors. Particularly recommended is [21], which provides up-to-date information on the use, care and maintenance of coaxial connectors as well as performance and specification figures. Related information can also be found in [22] and [23], although these documents are now obsolete and hence difficult to obtain. Excellent reviews of coaxial connector technology, both past and present, have been given in [24] and [25]. The following information is based on the above documents and other similar sources.

3.1 Types of Coaxial Connectors

There are several ways of categorising coaxial connectors – for example, as either sexed or sexless, or, as precision or non-precision. These categories are explained below, along with the GPC and LPC categories used for precision connectors.

3.1.1 Sexless and sexed connectors. (a) Sexless connectors. A connector is said to be "sexless" when both halves of a mated pair are nominally identical (both electrically and mechanically) and hence look the same. In recent times, the two most common sexless connectors are the 14 mm and 7 mm connectors. However, during the evolution of coaxial connector designs in the 1960s [26], other sexless connectors were produced (see, for example, [27]), but these are less common today. A schematic diagram of a generic sexless connector pair is shown in Figure 1. This diagram shows the principle components of the connector, i.e. the centre and outer conductors, the centre conductor's spring contact and the outer conductor reference plane. Notice that the position of the centre conductor is recessed with respect to the outer conductor reference plane. The spring contact thus ensures that good electrical contact is made between the centre conductors of a mated pair of sexless connectors.

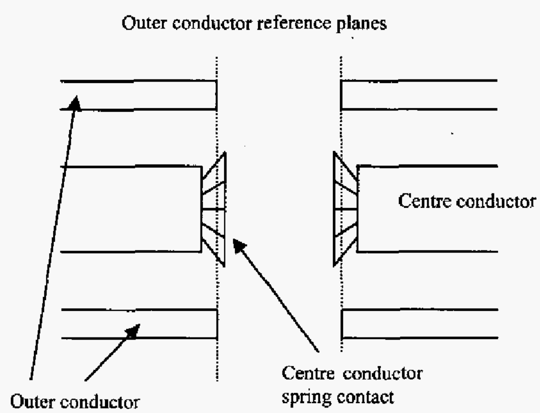

Figure 1: schematic diagram of a generic sexless connector pair

(b) Sexed connectors. The vast majority of connectors in current use are of the so-called "sexed" variety. These connectors use a male and female (i.e. pin and socket) arrangement to produce a mated pair. The most common examples of these connectors are the SMA, BNC and Type-N. However, these connector types are not generally of the precision variety (see section 3.1.2, below). A schematic diagram of a generic sexed

[4] The term RF is used in these notes to indicate frequencies ranging typically from 1 MHz to 1 GHz. In general, the term RF does not define a specific frequency region. Therefore, this term might be used in other texts to indicate different frequency regions.

connector pair is shown in Figure 2. This diagram is similar to Figure 1, except that the centre conductors' spring contacts are replaced by the pin (male) and socket (female) arrangements used for making the contact between the centre conductors of a mated pair of sexed connectors.

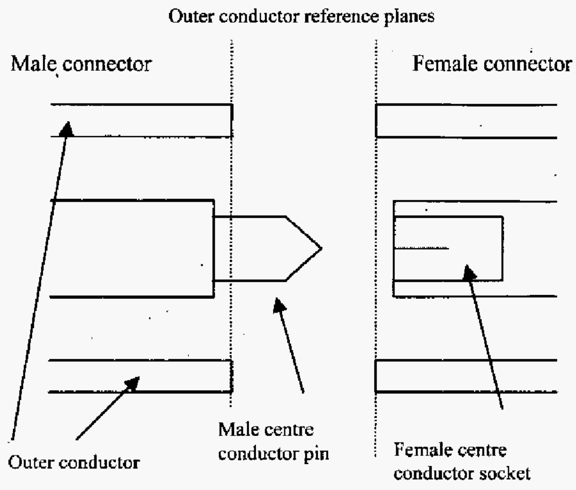

Figure 2: Schematic diagram of a generic sexed connector pair

3.1.2 Precision and non-precision connectors. (a) Precision connectors. The term 'precision' was used originally to describe only the sexless variety of connectors [28]. However, this category was later modified to include sexed connectors exhibiting very good electrical performance and coincident mechanical and electrical reference planes [29] (e.g. the 3.5 mm connector). These days, the term is generally used for high quality connectors having air as the dielectric at the connectors' reference planes.

The two precision sexless connectors are the 7 mm and 14 mm connectors mentioned above. Precision sexed connectors include the 3.5 mm, 2.92 mm, 2.4 mm, 1.85 mm and 1 mm connectors. The 2.92 mm and 1.85 mm connectors are often called the K- and V-connectors, respectively. In addition, there is a precision version of the Type-N connector[5] although the reference planes for the male and female sexes of this connector are not coincident.

Another major development in the acceptance of the above sexed connectors as being suitable for use as precision connectors has been the introduction of the slotless female contact. Conventional female connectors have longitudinal slots cut into the centre conductor that enable the pin of the male connector to be held tightly during mating. This provides a secure connection but also produces electrical discontinuities due to the slotted gaps in the female centre conductor and diameter variations, also in the female centre conductor, due to the diameter variations of male pins. The slotless female contact [30] avoids these two problems by placing the female's grasping mechanism inside the female centre conductor socket. The removal of the electrical discontinuities caused by the slotted arrangements means that slotless sexed connectors with a very high performance can be achieved (i.e. rivalling the performance of the sexless connectors).

However, devices fitted with slotless female contacts are generally more fragile, and more expensive, than the equivalent slotted devices and are therefore generally only used in applications requiring the very highest levels of measurement accuracy. Slotless female contacts can be found on Type-N, 3.5 mm and 2.4 mm precision connectors. There is also a special version of the 3.5 mm connector (called a WSMA [31]), which uses a slotless female contact, designed specifically to achieve good quality mating with SMA connectors.

(b) Non-precision connectors. There is a very large number and variety of non-precision coaxial connectors in use today. Some of the more popular non-precision connectors include the SMA, BNC, Type-N[6], UHF, TNC, SMC and SMB connectors. The scope of these notes does not include non-precision connectors, so no further details are given for these connectors.

3.1.3 GPC and LPC terminologies. The precision connectors, discussed above, can be further classified in terms of either GPC (General Precision Connector) or LPC (Laboratory Precision Connector) versions. GPCs include a self-contained solid dielectric element (often called a "bead") to support the centre conductor of the connector, whereas LPCs use only air as the dielectric throughout. The LPC therefore requires that the centre conductor of the connector is held in place by some other means. For example, the centre conductor of a reference air line fitted with LPCs can be held in place by the test ports of a measuring instrument to which the line is connected. LPCs are used where the very highest levels of accuracy are required (e.g. at national standard level). LPCs and GPCs for the same line size are mechanically compatible (i.e. they are of nominally the same cross-sectional dimensions).

The use of the terms GPC and LPC also avoids any confusion caused by using manufacturers' names to identify specific connectors. For example, using the term APC-7 implies a connector manufacturer

[5] In fact, there are a considerable number of different qualities of Type-N connector of which most would not be classified as "precision". Therefore, care should be taken when using different varieties of Type-N connectors so that the overall desired performance of a measurement is not compromised.

[6] The Type-N connector is included in lists of both precision and non-precision connectors due to the wide range of performance for this connector (depending on the connector specification), as mentioned previously.

(e.g. Amphenol) but does not necessarily indicate whether the connector is an LPC-7 or GPC-7 version.

3.2 Mechanical Characteristics

Two very important mechanical characteristics of a coaxial connector are its size (i.e. the diameters of the two coaxial line conductors) and mating compatibility with other connectors. Table 2 gives the nominal sizes of the precision connectors discussed previously.

TABLE 2 - line diameters of precision connectors

Connector name	Line size, i.e. the outer conductor internal diameter (mm)	Centre conductor diameter (mm)
14 mm (e.g. GR900) [7]	14.2875	6.204
7 mm (e.g. APC-7)	7.000	3.040
Type-N	7.000	3.040
3.5 mm	3.500	1.520
2.92 mm (K-connector)	2.920	1.268
2.4 mm	2.400	1.042
1.85 mm (V-connector)	1.850	0.803
1 mm	1.000	0.434

Several of the above connector types have been designed to be mechanically compatible with each other, meaning that they can mate with other types of connector without causing damage. Specifically, 3.5 mm connectors can mate with K-connectors, and 2.4 mm connectors can mate with V-connectors. This is achieved by using the same diameter for the male pin of the connector (as shown in Table 3). However, since the diameters of the coaxial line sections in the connectors are of different sizes (as shown in Table 2) there will be an electrical discontinuity at the interface between a mated pair of these mechanically compatible connectors. This discontinuity is caused by the step changes in the diameters of both the centre and outer conductors of the coaxial line and can be represented electrically as a single shunt capacitance at the reference plane of the connector pair [32]. This discontinuity capacitance produces a reflection at the connector interface that varies with frequency. This effect has been investigated in [33], and typical maximum values for this reflection are given in Table 3.

TABLE 3 - electrical discontinuities caused by joining mechanically compatible connectors

Connector pair	Centre conductor pin diameter for both connectors (mm)	Equivalent discontinuity capacitance (fF)	Maximum linear reflection coefficient magnitude
3.5 mm and K-connector	0.927	8	0.04 (at 33 GHz)
2.4 mm and V-connector	0.511	10	0.08 (at 50 GHz)

In addition to the mechanical compatibility of the above precision connectors, the 3.5 mm and K-connectors are also mechanically compatible with the SMA connector. In this case, the presence of a solid dielectric (e.g. Teflon) at the reference plane of the SMA connector causes an additional discontinuity capacitance (this time due to the dielectric) leading to even larger electrical reflections than those produced from a 3.5 mm to K-connection. However, as mentioned previously, the WSMA precision 3.5 mm connector was designed specifically to produce high performance mating with SMA connectors [31]. This is achieved by deliberately setting back the position of the centre conductor pin by a prescribed amount, and hence introducing an amount of inductance to compensate for the additional capacitance caused by the SMA's dielectric [34].

3.3 Electrical Characteristics

Two very important electrical characteristics of a coaxial connector are the nominal characteristic impedance and the maximum recommended operating frequency to ensure a stable, and repeatable, measurement. The characteristic impedance of coaxial air lines is discussed in detail in section 4 of these notes. This discussion is also applicable to the precision coaxial connectors used with these air lines.

The maximum recommended operating frequency for a coaxial line is usually chosen so that only a single electromagnetic mode of propagation is likely to be present in the coaxial line at a given frequency. This is the dominant Transverse Electro-Magnetic (or, TEM) mode and operates exclusively from DC to the maximum recommended operating frequency. Above

[7] This connector actually has an outer diameter of 14.2875 mm, and not 14 mm as its name implies. This is because the original connector design was based around an outer diameter of 9/16". When the connector was standardised, it was decided to keep the diameter as 14.2875 mm (9/16") but to use a less precise name (i.e. 14 mm).

this frequency, other higher order modes[8] can also propagate to some extent.

The maximum recommended operating frequency is often called the "cut-off frequency" as it corresponds to the lower frequency cut-off for these higher order waveguide modes. The first higher order mode in 50 ohm coaxial line is the TE_{11} mode (also known as the H_{11} mode, in some references). The cut-off frequency is given by [35]:

$$f_c = \frac{c}{\lambda_c \sqrt{\mu_r \varepsilon_r}}$$

It has been shown in [36] that the approximate cut-off wavelength for the TE_{11} mode is given by:

$$\lambda_c \approx \pi(a+b)$$

which corresponds to the average circumference of the line's conductors. More precise expressions for the cut-off wavelength can be obtained from [37] and these produce the theoretical upper frequency limits (i.e. the cut-off frequencies) for each line size shown in Table 4, below.

TABLE 4 - theoretical and recommended upper frequency limits for coaxial connectors

Connector name	Theoretical upper frequency limit (GHz)	Recommended usable upper frequency limit (GHz)
14 mm (e.g. GR900)	9.5	8.5
7 mm (e.g. APC-7)	19.4	18.0
Type-N	19.4	18.0
3.5 mm	38.8	33.0
2.92 mm (K-connector)	46.5	40.0
2.4 mm	56.5	50.0
1.85 mm (V-connector)	73.3	65.0
1 mm	135.7	110.0

[8] These modes are often called "waveguide modes" since they are similar to the modes found in hollow waveguide. These modes are either Transverse Electric (TE) or Transverse Magnetic (TM) and have a longitudinal component to their propagation. It should be noted that the TEM mode can continue to propagate at frequencies where TE and TM modes are also possible, since the TEM mode does not actually have an upper frequency limit.

Table 4 also gives recommended usable upper frequency limits for each line size. These are lower than the theoretical upper frequency limits and this is due to potential higher-order-mode resonances (again, the TE_{11} mode being the most likely) caused by solid material dielectric (e.g. Teflon) being present between the two conductors of the coaxial line. These resonances are most problematic when they occur in the vicinity of the transitions from air to solid dielectric, such as when a dielectric bead is used to support the centre conductor of the coaxial line (as in GPCs). Such resonances can occur in single connector beads as well as in a mated connector pair containing two dielectric beads.

These higher-order-mode resonances can cause significant electromagnetic changes in both the reflection and transmission properties of the coaxial line. (In general, these changes cause the reflection coefficient of the line to increase whereas the transmission coefficient decreases.) These resonances are highly unpredictable and can be initiated by subtle asymmetries, eccentricities or other irregularities that may be present in the line – as can be the case at connector interfaces. For example, if dielectric beads form part of the connector interface (as in GPCs), these electromagnetic changes can vary according to the orientation of the connectors each time a connection is made. Under these conditions, even pristine precision connectors can exhibit very poor repeatability of connection.

The presence of bead resonances in precision coaxial connectors has been investigated in [38], while [39] presents some methods proposed to reduce the likelihood of excitation of these modes (e.g. through connector bead design). In any case, care should be taken when performing measurements near the upper frequency limits of coaxial connectors – even the recommended usable upper frequency limits, given above. Acute changes in the reflection and transmission coefficients (or a lack of repeatability of these coefficients) may indicate the presence of a higher-order mode resonance.

4 AIR LINES

Precision air dielectric coaxial transmission lines (or, air lines, for short) can be used as reference devices, or standards, for impedance measurements at RF and microwave frequencies. (The term impedance is used here to imply a wide range of electrical quantities, such as S-parameters, impedance and admittance parameters, VSWR, return loss, etc.) This includes the use of air lines as calibration and verification standards for measuring instruments such as Vector Network Analysers (VNAs) [40]. For example, VNA calibration schemes, such as Thru-Reflect-Line (TRL) [41] and Line-Reflect-Line (LRL) [42], use air lines as standards to achieve very high accuracy impedance measurement capabilities. This is the method currently used to realise the UK primary national standard for impedance quantities [43] at RF and microwave frequencies (typically, from 45 MHz and above). Similarly, verification schemes determining the residual systematic errors in a calibrated VNA [44] use air lines as the reference devices, and these methods are currently endorsed by organisations involved in the accreditation of measurement, such as the European co-operation for Accreditation (EA) [45].

This section describes the different types of air line that are available and reviews their use as standards of characteristic impedance and/or phase change. Consideration is also given for the effects caused by imperfections in the conductors used to realise these air lines.

4.1 Types of Precision Air Line

There are basically three types of air line depending on the number of dielectric beads used to support the centre conductor of the line. These beads are usually to aid in the connection of the line during measurement.

4.1.1 Unsupported air lines. These lines do not contain any support beads and therefore the connector interfaces conform to the LPC category. The ends of the centre conductor are usually fitted with spring-loaded contacting tips to facilitate connecting the line to other connectors. The line's centre conductor is held in place by the test ports of a measuring instrument (or whatever else is being connected to the line). The centre and outer conductors of these lines come in two separate parts and are assembled during connection. These lines (which are of a calculable geometry) are used where the very highest levels of accuracy are required. Therefore, such lines are often found in VNA calibration kits used to realise TRL and LRL calibration schemes.

4.1.2 Partially supported air lines. These lines contain a support bead at only one end of the line. This design is often used for relatively long lengths of line that may be difficult to connect if they were not supported in some way. The unsupported end of the line is usually connected first – this being the more difficult of the two connections – followed by the supported end (which connects like a conventional connector). Such a line therefore has connections that are LPC at one end and GPC at the other. The centre and outer conductors of these lines often come as two separate components, although fully assembled versions also exist where the centre conductor is held in place by the bead in the air line's GPC. Semi-supported lines are often found in VNA verification kits where a calculable geometry is not required (although a high electrical performance is still necessary). These lines can also be used in applications where minor reflections from one end of the line do not cause problems (e.g. some applications of the 'ripple' technique [44]).

4.1.3 Fully supported air lines. These lines contain support beads at both ends of the line. This is equivalent to GPCs being present at both ends of the line thus making it relatively easy to connect. These lines come fully assembled with the centre conductor being held in place by both beads in the air line's GPCs. Such lines find application where only relatively modest levels of accuracy are required or where only a part of the length of a line needs to be of a known, or calculable, impedance (e.g. when calibrating time-domain reflectometers). In such applications, the minor reflections and discontinuities caused by the presence of the beads will be inconsequential.

4.2 Air Line Standards

In the above applications, the air lines are used as references of either characteristic impedance or phase change, or both. These two applications are discussed below.

4.2.1 Characteristic impedance. In general, the characteristic impedance of a particular electromagnetic mode supported by a coaxial line is a complex function of the dimensions and alignment of the conductors, the physical properties of the materials of the line, and the presence of discontinuities such as connectors. However, for a uniform line with lossless conductors and air between the centre and outer conductors, the characteristic impedance of the TEM mode can be approximated by:

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\log_e\left(\frac{b}{a}\right) \approx 59.93904 \times \log_e\left(\frac{b}{a}\right)$$

From the above expression, it is clear that the characteristic impedance of a line can be found from measurements of the diameters of the line's conductors. Such measurements are often made using air gauging techniques [46] that enable measurements to be made continuously along the entire lengths, and at all possible orientations, of both conductors. This is a very useful technique since the determination of an air line's characteristic impedance can be made with direct traceability to the SI base unit of length (i.e. the metre).

Similarly, it is also clear that, from the above expression, values of characteristic impedance can be established by using different diameters for a line's conductors. This is evident from the diameter values presented in Table 2 that show a range of diameter values for coaxial air lines each with a nominal characteristic impedance of 50 ohms. Similarly, Table 5 gives diameter values that achieve a nominal characteristic impedance of 75 ohms for the 14 mm and 7 mm line sizes, mentioned previously. These diameters are used to realise 75 ohm versions of the GR900 and Type-N connectors, respectively[9].

TABLE 5 - line diameters for 75 ohm line sizes

Connector name	Line size, i.e. the internal diameter of the outer conductor (mm)	Centre conductor diameter (mm)
GR900	14.2875	4.088
Type-N	7.000	2.003

Having established that a wide range of characteristic impedance values can be achieved simply by choosing different diameters for the centre and outer conductors, this raises the question; "why is 50 ohms a preferred value for the characteristic impedance of coaxial lines?" The answer appears to be that it was chosen as a compromise in performance between the theoretical characteristic impedance needed to obtain minimum attenuation in a line (which occurs at nominally 77.5 ohms[10]) and the theoretical characteristic impedance needed to obtain the maximum power transfer along a line (which occurs at nominally 30 ohms). The average of these two values is 53.75 ohms, which rounds to 50 ohms (to one significant figure). Hence, 50 ohms is a good compromise value for the characteristic impedance of lines used in many and diverse applications.

4.2.2 Phase change. Air lines can also be used as standards of phase change since a lossless line will only introduce a phase change to a signal, which relates directly to the line's length. The phase change is given by:

$$\Delta\varphi = 2\pi \frac{\sqrt{\varepsilon_r}}{c} f\, l \quad \text{(radians)}$$

or

$$\Delta\varphi = 360 \frac{\sqrt{\varepsilon_r}}{c} f\, l \quad \text{(degrees)}$$

Air lines have been used successfully as phase change standards to calibrate reflectometers and VNAs at the very highest levels of accuracy (see, for example, [47, 48]). These techniques use the lines in conjunction with high reflecting terminations (such as short-circuits and open-circuits) to produce a known phase change at the instrument test port. In recent years, the use of such techniques is beginning to re-emerge in applications where it is not practical to use unsupported air lines primarily as standards of characteristic impedance (e.g. in calibration schemes such as TRL and LRL). For example, a kit currently available for VNA calibrations in the 1 mm coaxial line size [10] uses short-circuits offset by different lengths of line to achieve calibrations from around 50 GHz to 110 GHz.

An important consideration when using air lines in conjunction with high reflecting terminations (e.g. as offset short-circuits) is that the effective electrical length of the offset line is actually double the mechanical length. This is because the electrical signal has to make a 'there-and-back' journey along the length of the line having been reflected back from the termination at the end of the line.

4.3 Conductor Imperfections

In the above discussion concerning using air lines as standards of characteristic impedance and phase change, it has been assumed that the line's conductors are made of lossless material (i.e. the conductors are perfectly conducting or, in other words, possess infinite conductivity). However, in practice, conductors are not perfectly conducting and therefore possess finite conductivity (or loss). This causes problems for the electrical properties of lines especially at low frequencies when the conductivity at the surface of the conductors becomes important. Manufacturers attempt to minimise these problems by producing lines made of very high conductivity materials (such as alloys of copper) or by applying a plating layer of high conductivity material (such as silver) to the surface of the conductors in the coaxial line.

Even so, as frequency decreases, the finite conductivity of a line causes the propagating wave to penetrate the walls of the conductors to some extent. The attenuation constant associated with the wave propagating into the walls of the conductors[11] is considerably higher than for the wave propagating in the dielectric between the conductors, and therefore the wave attenuates rapidly as it penetrates the walls of the conductors. The reciprocal of this attenuation constant is called the skin depth and is defined as the distance travelled into the walls of the conductors by the wave before being attenuated by one neper (≈ 8.686 dB).

[9] **Caution!** Great care should be taken when performing measurements where both 75 ohm and 50 ohm versions of the same connector type are available. For the Type-N connector, damage will occur to a 75 ohm female connector if an attempt is made to mate it with a 50 ohm male connector. This is due to the substantial difference in diameters of the male pin and the female socket. (Note that the same situation occurs with 50 ohm and 75 ohm versions of BNC connectors!)

[10] This may also explain why 75 ohms is also often used in some applications (such as in certain areas of the communications industry).

[11] The wave decays exponentially as it penetrates the walls of the conductors.

The skin depth is given by:

$$\delta_s = \sqrt{\frac{1}{\pi f \sigma \mu}}$$

This indicates that skin depth increases as the frequency decreases. The skin depth will also be larger for a line with a lower value of conductivity. To illustrate this, values for skin depth are given in Table 6, for conductors made of silver, brass and beryllium copper (BeCu), with assumed conductivities of 62 MS.m^{-1}, 16 MS.m^{-1} and 13 MS.m^{-1}, respectively, as these are materials often used to fabricate precision air lines. Further detailed discussions on skin depth effects can be found in [49].

TABLE 6 - skin depth values as a function of frequency.

Frequency (MHz)	Skin depth (μm)		
	Silver (σ = 62 MS.m^{-1})	Brass (σ = 16 MS.m^{-1})	BeCu (σ = 13 MS.m^{-1})
1	64	126	140
10	20	40	44
100	6	13	14
1 000	2	4	4

It is generally only necessary to accurately determine the conductivity of a line's conductors at RF (typically, between 1 MHz and 1 GHz) in order to determine the line's characteristics. This is because lines are rarely used as impedance standards below these frequencies and skin depth becomes less of a problem at higher frequencies. This requirement, however, is not trivial. If the line's constitution is known then a value may be obtained from tables of physical data (e.g. from sources such as [50]). However values specified in tables usually refer to bulk material samples. These values are often different from actual values for the same material after it has been subject to manufacturing processes, as is the case for air lines (see, for example, [51, 52]).

An additional problem in determining a value for the conductivity of a line is caused by plating layers that may be applied by manufacturers either to increase conductivity (e.g. silver plating) or increase longevity (e.g. gold 'flashing'). Several studies have been carried out evaluating effects of plating on the effective conductivity of conductors [53-55] but these assume prior knowledge of the material of each layer and ignore additional complications caused by impurities which will doubtlessly be present. A recent validation of theoretical predictions based on assumed conductivity values has been performed by comparison with precision attenuation measurements [56].

Finally, another consideration concerning the characteristics of a line relates to the non-uniformity of the conductors' surfaces caused either by changes in the longitudinal dimensions of the line [57, 58] or surface roughness [59]. In both cases, these effects will cause the properties of the line to depart significantly from ideal values.

5 RF IMPEDANCE

The measurement of impedance, and impedance related quantities, requires special consideration when the measurement frequency is in the RF region (i.e. from 1 MHz to 1 GHz). This is generally due to techniques used at the higher frequencies becoming inappropriate at these longer wavelengths. Similarly, low frequency techniques, used below 1 MHz, are also unsuitable – for example, because the connector configurations are often different (e.g. four-terminal pair connections, etc). Information is given below concerning using air lines and terminations (i.e. one-port devices) as impedance standards at RF – for example, to calibrate a VNA. More detailed information can be found in [60].

5.1 Air Lines

Air lines can be used in conjunction with terminations as calibration items for reflectometers (or VNA one-port calibrations). In this configuration, one end of the air line is connected to the instrument test port while the other end is connected to the termination. Lines can also be used for VNA two-port calibrations (such as TRL and LRL, where they act as the Line standard) and are connected between the two test ports during calibration. In either application, the accuracy achieved using modern VNAs requires that the electrical characteristics of the air lines are defined very precisely, as shown below.

A coaxial line can be characterised using the distributed circuit model given in Figure 3, where R, L, G and C are the series resistance and inductance, and the shunt conductance and capacitance, respectively, per unit length of line.

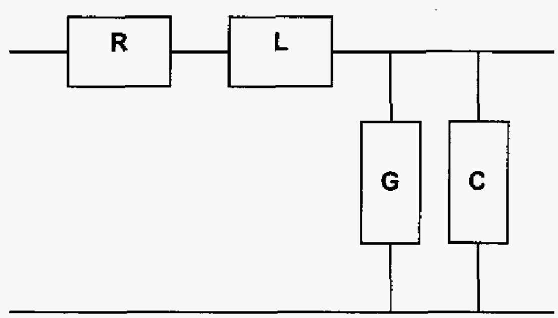

Figure 3: Distributed circuit model for a section of coaxial line

Expressions for the four line elements R, L, G and C can be used to obtain further expressions for two fundamental line parameters – the characteristic impedance and the propagation constant – which are defined as follows:

$$Z = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}}$$

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

5.1.1 Lossless lines. For a lossless line (i.e. with conductors of infinite conductivity) the series resistance and the shunt conductance are both zero. The series inductance and the shunt capacitance have fixed values independent of frequency and are given by:

$$L_0 = \frac{\mu \log_e (b/a)}{2\pi}$$

$$C_0 = \frac{2\pi\varepsilon}{\log_e (b/a)}$$

The characteristic impedance of the lossless line is therefore (as before):

$$Z_0 = \sqrt{\frac{L_0}{C_0}} = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}} \log_e\left(\frac{b}{a}\right)$$

This shows that the line's characteristic impedance is a purely real quantity (i.e. containing no imaginary component), is independent of frequency and, determined by the ratio (b/a). For example, to achieve a characteristic impedance of 50 ohms this ratio is approximately 2.3.

The propagation constant of the lossless line is:

$$\gamma_0 = j\beta = j\omega\sqrt{L_0 C_0} = j\omega\sqrt{\mu\varepsilon} = j\frac{\omega}{v} = j\frac{2\pi}{\lambda} \text{ (rad.m}^{-1}\text{)}$$

This shows that the line's propagation constant is purely imaginary (i.e. containing no real component) and is determined only by the wavelength (or equivalent) of the propagating wave. The attenuation constant is zero which is consistent with a line having no loss. The phase constant is a linear function of frequency, indicating a non-dispersive line.

5.1.2 Lossy lines. As mentioned previously, metallic air-filled coaxial lines are not lossless. An important part of line characterisation at RF is a determination of the effects due to line loss. An attempt at dealing with this problem for RF impedance standardisation has been given in [61]. Further work has since been presented in [62], giving expressions for all four line elements – R, L, C and G – containing frequency dependent terms for each element. Additional work has also solved this problem for frequencies below the RF region, obtaining exact field equations for lossy coaxial lines [63].

The expressions derived in [62] for the four line elements at RF are as follows:

$$R = 2\omega L_0 d_0 \left(1 - \frac{k^2 a^2 F_0}{2}\right)$$

$$L = L_0 \left[1 + 2d_0 \left(1 - \frac{k^2 a^2 F_0}{2}\right)\right]$$

$$G = \omega C_0 d_0 k^2 a^2 F_0$$

$$C = C_0 (1 + d_0 k^2 a^2 F_0)$$

where:

$$F_0 = \frac{(b^2/a^2) - 1}{2\log_e (b/a)} - \frac{(b/a)\log_e (b/a)}{(b/a) + 1} - \frac{1}{2}\left[\frac{b}{a} + 1\right]$$

$$d_0 = \frac{\delta_s (1 + (b/a))}{4b \log_e (b/a)}$$

These expressions can be used to calculate the characteristic impedance, which, for a line with finite conductivity, is clearly a complex quantity, material dependent and a function of frequency. Figures 4 and 5 illustrate the effect on the characteristic impedance of a nominal 50 ohm 7 mm air line made of BeCu with an assumed conductivity of 13 MS.m^{-1}.

The deviation in the characteristic impedance causes a problem for impedance measurements (such as S-parameters) since they are usually specified with respect to the lossless line value (e.g. 50 ohms). Measurements made on instruments calibrated with lines of different material will vary systematically since the impedance parameters will be measured with respect to different characteristic impedances. This problem is overcome by transforming from the actual line characteristic impedance to the defined lossless value (e.g. 50 ohms, for the 50 ohm line size). Further information on impedance transformations of this type is given in [64].

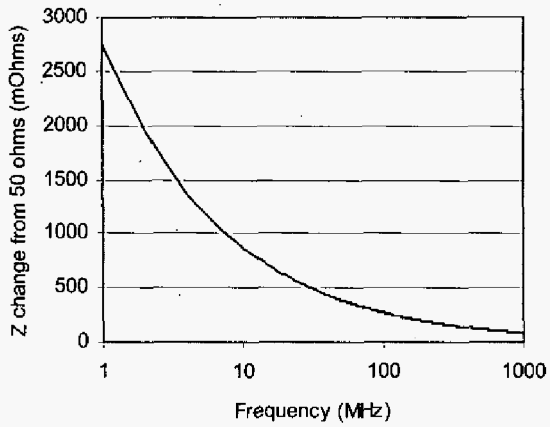

Figure 4: Change in characteristic impedance magnitude for a 7 mm BeCu line.

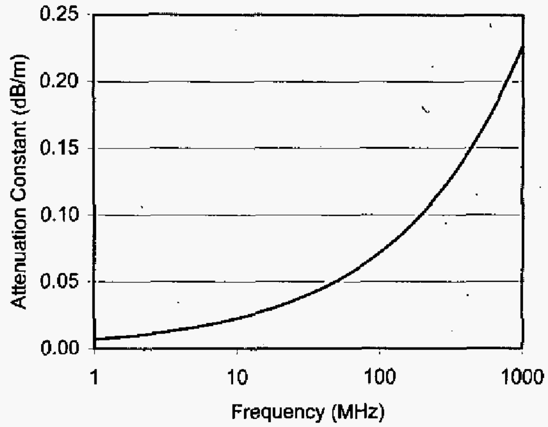

Figure 6: Attenuation constant for a 7 mm BeCu line.

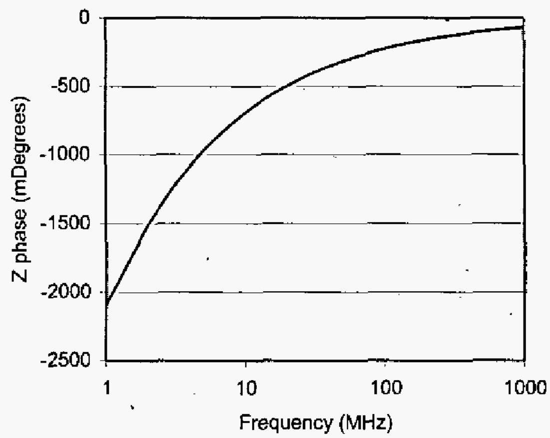

Figure 5: Characteristic impedance phase angle for a 7 mm BeCu line.

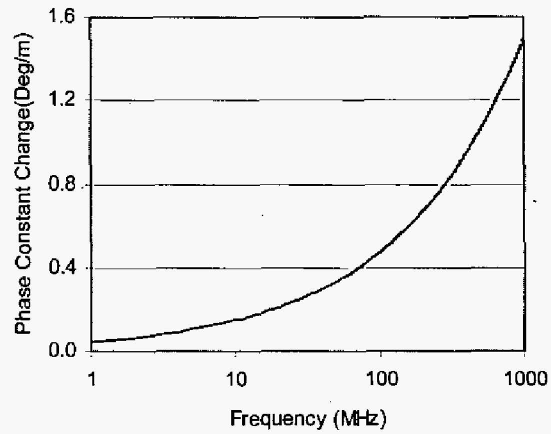

Figure 7: Change in phase constant for a 7 mm BeCu line.

The above expressions can also be used to calculate the propagation constant, which, for a line with finite conductivity has both real and imaginary parts and is non-linear with frequency. Figures 6 and 7 illustrate the effect on the propagation constant for a nominal 50 ohm 7 mm air line made of beryllium copper. The attenuation constant is non-zero (Figure 6), which is consistent with a line containing loss. The increase in the phase constant from its lossless value indicates that the line's electrical length is longer than its physical length – this discrepancy varying as a function of frequency. The line is therefore dispersive and imparts group delay to broadband signals.

A comparison of parameters characterising lossless and lossy lines reveals that only one extra term is included to allow for the loss effects – i.e. the conductors' conductivity. If the conductivity is assumed to be infinite, the skin depth becomes zero and the term d_0 in the expressions for the four lossy line elements vanishes. This causes R and G to become zero and L and C to revert to their lossless values (i.e. L_0 and C_0). The finite conductivity (and hence non-zero skin depth) of the conductors is therefore solely responsible for departures from the lossless line conditions. The expression given earlier for skin depth also contains a $1/\sqrt{f}$ term indicating that skin depth increases as frequency decreases, causing a subsequent increase in the values for all four line elements.

5.2 Terminations

It is often very convenient to use terminations (i.e. one-port devices) as calibration standards for reflectometers and VNAs. These terminations can be used in both one-port and two-port VNA calibration schemes. The terminations can be connected directly to the instrument test port or separated by a length of air line called an "offset". The air line section can be an integral part of the item or connected separately. The three most common terminations used for this purpose are short-circuits, open-circuits and near-matched terminations (including so-called sliding loads). Mismatched terminations (and capacitors) can also be used, particularly at lower frequencies.

5.2.1 Short-circuits. A coaxial line short-circuit is simply a flat metallic disc connected normally to the line's centre and outer conductors. Its radius must exceed the internal radius of the outer conductor and be of sufficient thickness to form an effective shield for the electromagnetic wave propagating in the line. The disc is usually made of a similar material as the line's conductors. Short-circuits can be connected directly to an instrument test port or via a length of line producing an offset short-circuit.

Short-circuits provide a good approximation to the lossless condition at RF (i.e. with both series resistance and inductive reactance being close to zero). This produces a reflection coefficient with real and imaginary parts of −1 and 0, respectively. Loss due to skin depth and surface finish of the disc can be considered for high precision metrology applications. Such losses have been considered in [65] by analysing the effects of a TEM wave incident normally to a conducting plane.

5.2.2 Open-circuits. In principle, a coaxial open-circuit is produced by having nothing connected to the instrument test port. However, this produces a poorly defined standard, for two reasons: (i) it will radiate energy producing a reflected signal dependent on obstacles in the vicinity of the test port; and (ii) the test port connector's mating mechanism affects the established measurement reference plane which limits accurate characterisation as a standard.

The first of these problems can be overcome by extending the line's outer conductor sufficiently beyond the position of the open-circuited centre conductor so that the evanescent radiating field decays to zero within the outer conductor shield – the extended outer conductor acting as an effectively infinite length of circular waveguide below cut-off.

The second problem can be overcome either by depressing the mating mechanism using a dielectric plug or attaching a length of line to the centre conductor, terminated in an abrupt truncation. The dielectric plug technique is used as a standard with numerous VNA calibration kits. The abruptly truncated line technique has been used to realise primary national impedance standards [47, 66]. In both cases, the open-circuit behaves as a frequency dependent 'fringing' capacitance. Calculations for the capacitance of an abruptly truncated coaxial line can be found in the literature (for example, [67-69]). These values have been verified for RF impedance applications using a computer-intensive equivalent circuit technique [70].

Coaxial open-circuits have a reflection coefficient of nominally unity magnitude and a phase angle dependent on the fringing capacitance and the length of any line used to fabricate the device. They can therefore be very useful as standards for calibrating reflectometers and VNAs.

5.2.3 Near-matched terminations. A low reflection (or near-matched) termination can be produced by mounting a cylindrical thin-film resistive load in the centre conductor of a line with a tractorially-shaped outer conductor. A parabolic transition between the conventional coaxial line and the tractorial section transforms incident plane wave fronts to spherical wave fronts required to propagate in the tractorial section of the termination. This produces near-uniform power dissipation along the length of the resistive load element with minimal frequency dependence. This design of low reflecting termination has been discussed in [71].

Low reflection terminations are usually assumed to have zero reflection during a reflectometer, or VNA, calibration (and are therefore often called 'matched' loads). Alternatively, low reflecting load elements can be used to 'synthesise' the performance of a matched termination, using sliding load techniques. This is achieved by measuring the response of a load element at several positions along a variable length of precision air line. The characteristics of a 'perfectly' matched termination can then be computed by fitting a circle to the measured reflection values (the centre of the fitted circle being the point in the complex reflection coefficient plane corresponding to a perfect match, i.e. zero reflection). However, problems due to imperfections in the air line section and inadequate phase differences produced by realisable lengths of air line make this technique of limited use at RF.

5.2.4 Mismatched terminations. In principle, mismatched terminations (and capacitors) can be very useful devices for providing values of reflection that are significantly different from those achieved using short-circuit, open-circuit and near-matched terminations. Such reflection values could be used in certain calibration applications (e.g. as alternatives to the short-open-load values used during conventional VNA calibration schemes). However, devices used for calibration (i.e. standards) are usually assumed to have 'known' values based on either a calculated and/or measured performance[12]. In general, it is not possible to calculate, to any degree of accuracy, the performance of a mismatched termination. Indeed, the same can be said of near-matched terminations where an assumed value (i.e. zero) is often used for calibration purposes.

There have been several attempts recently at characterising near-matched terminations using measurement data at DC and RF. Some work in the 1990s [72] used equivalent circuit models for characterising these devices at lower RF (300 kHz to 30 MHz) based on measurement data at higher RF. More recent work [73, 74] has concentrated on implementing interpolation schemes for characterising these devices. The interpolation schemes have the advantage that very few assumptions need to be made concerning the characteristics of the device. In principle, such schemes can be extended to characterise 'any' device (e.g. mismatch terminations) without requiring detailed knowledge concerning the physical (i.e. calculable) properties of the device. This is leading to the development of generalised techniques for VNA calibrations [75] that do not need to rely on the classical assumptions implicit in the short-open-load calibration schemes. Such techniques are expected to greatly enhance our knowledge of calibration devices and instruments used traditionally to perform RF impedance measurements.

6 FUTURE DEVELOPMENTS

Coaxial connectors and coaxial transmission lines continue to play a crucial role in the realisation of the majority of measurements made at RF and microwave frequencies. These notes have presented some of the important issues relating to the various types of coaxial connector currently available for making high precision measurements. Even so, the connector itself can still be the limiting factor for the accuracy achieved by today's measurement systems.

Similarly, coaxial air lines provide very useful standard reference artefacts for realising impedance quantities for these connector types and the associated transmission lines. These devices are simple structures with well-defined electromagnetic properties. But once again, the precision at which today's instruments can operate means that these standards will need to be defined to an even greater level of precision. This is particularly true at lower RF (and, indeed, at extremely high frequencies) where the lines' characteristics depart substantially from their idealised values.

[12] For example, the characteristics of unsupported air lines can be calculated based on the measured values of the diameters of the line's conductors.

It is unlikely that future requirements for these technologies will be less demanding than they are at present. Indeed, it can be expected that most measurement applications will require broader bandwidths, improved electrical capabilities (including repeatability, insertion loss and lower passive inter-modulation) and higher levels of accuracy. These demands are likely to continue to drive developments in precision coaxial connectors, air lines and other impedance standards for the foreseeable future.

APPENDIX: 7/16 CONNECTORS

The 7/16 connector was developed during the 1960s primarily for high performance military applications. In recent years, it has become a popular choice for certain applications in the mobile communications industry, such as in base stations and antenna feed lines. This is due to its suitability for uses involving high power levels, low receiver noise levels and where there are requirements for low passive inter-modulation (PIM).

The 7/16 connector is a sexed connector with a nominal characteristic impedance of 50 ohms. It is available in both GPC and LPC versions – LPCs are found on 7/16 unsupported air lines used in VNA calibration kits to realise calibration schemes such as TRL and LRL. Terminations are also available which can be used for Short-Open-Load calibration schemes. The nominal diameters of the centre and outer conductors are 7 mm and 16 mm, respectively, and this yields a recommended usable upper frequency limit of approximately 7.5 GHz.

At present, there are ***no*** primary national standards of impedance for 7/16 connectors!

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