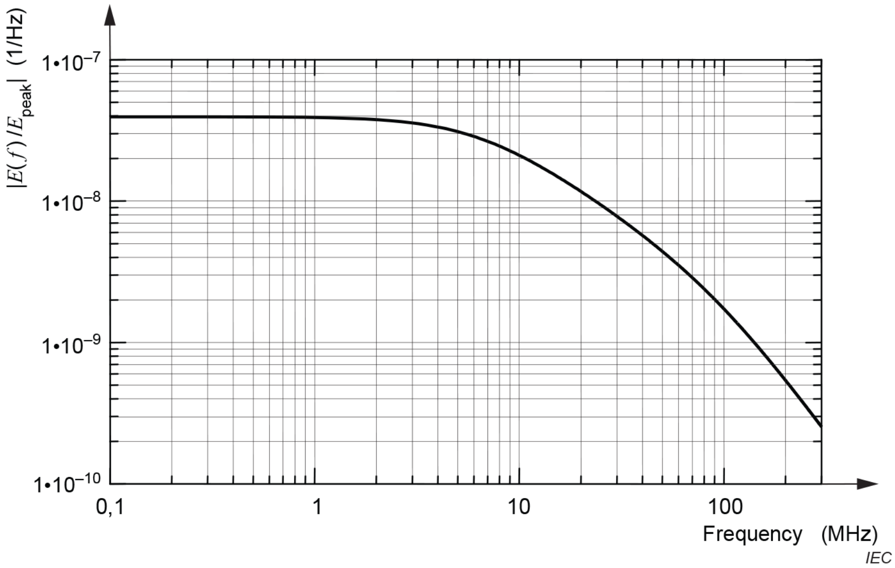
C.6 Figure for Annex C



NOTE Spectral magnitude is determined using the parameters listed after Equation (C.1) in Equation (C.2).

Figure C.1 – Pulse waveform frequency domain spectral magnitude between 100 kHz and 300 MHz (see C.2.1)

Annex D
(informative)

TEM waveguide characterization

D.1 Overview

Annex D describes the basic characteristics of a TEM wave, including the propagation and polarization aspects. Different categories of TEM waveguides are also presented, along with the limitations relative to test volumes and frequencies of operation.

D.2 Distinction between wave impedance and characteristic impedance

A TEM waveguide is a form of transmission line. The wave impedance and characteristic impedance of a loss-less transmission line are defined in [51] as follows.

The wave impedance η is defined as the ratio of the transverse field components, which can be calculated assuming an $e^{-j\beta z}$ dependence according to Equation (D.1)

$$\eta = \frac{E_\rho}{H_\varphi} = \frac{\omega\mu}{\beta} = \sqrt{\frac{\mu}{\varepsilon}} \tag{D.1}$$

where

η is the wave impedance;

E_ρ is the transverse component of the electric field;

H_φ is the transverse component of the magnetic field;

μ is the permeability of the transmission line dielectric (typically air);

ε is the permittivity of the transmission line dielectric (typically air);

β is the propagation constant (real part);

ω is the radiant frequency.

This wave impedance is then seen to be identical to the intrinsic impedance of the medium and is a general result for TEM transmission lines.

The characteristic impedance of a circular-cylindrical coaxial line is defined as

$$Z_\mathrm{c} = \frac{V_0}{I_0} = \frac{E_\rho \ln\frac{2h}{a}}{2\pi H_\varphi} = \eta \cdot \frac{\ln\frac{2h}{a}}{2\pi} = \sqrt{\frac{\mu}{\varepsilon}} \cdot \frac{\ln\frac{2h}{a}}{2\pi} \tag{D.2}$$

where

Z_c is the characteristic impedance of the coaxial line;

V_0 is the voltage of the coaxial line;

I_0 is the current of the coaxial line;

E_ρ is the transverse component of the electric field;

H_φ is the transverse component of the magnetic field;

h $2h = r_i$, r_i: radius of inner conductor;

a $a = r_a$, r_a:radius of outer conductor.

The forms for E_ρ and H_φ from [8] have been used. The characteristic impedance is geometry-dependent, and it will be different for other transmission line configurations.

Equations (D.1) and (D.2) show that in general the wave impedance and the characteristic impedance are not equal. Since TEM and gigahertz-TEM cells and two-plate and three-plate striplines are basically two-conductor TEM-mode transmission lines, in general the wave impedance and the characteristic impedance in those devices will also not be equal.

D.3 TEM wave

D.3.1 General

TEM waves are most easily described in terms of their behaviour in free space. Subclauses D.3.2 and D.3.3 present several equations and criteria for both the free-space and waveguide cases.

D.3.2 Free-space TEM mode

In a TEM mode both the electric and magnetic field vectors are entirely transverse to the direction of energy propagation (Poynting vector $\vec{S}$, according to Equation (D.3)). There is no component of either $\vec{E}$ or $\vec{H}$ in the direction of transmission.

$$\vec{S} = \vec{E} \times \vec{H} \tag{D.3}$$

For “free space” the ratio between $|\vec{E}|$ and $|\vec{H}|$ is given by

$$\eta_0 = \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 120\pi\,\Omega \tag{D.4}$$

The essential properties of the TEM mode are

– no field component in the direction of transmission;

– the ratio between $|\vec{E}|$ and $|\vec{H}|$ is nearly $120\pi\Omega$.

NOTE Far away from a transmitting antenna, the preceding situation exists; therefore, the TEM mode is often called the “far-field condition” of an antenna.

D.3.3 Waveguides

A classical waveguide for RF applications consists of only one closed conducting surface. It can be shown that a TEM mode cannot propagate within such a waveguide (see Figure D.1 in Clause D.8). Only TE and/or TM modes are possible. Because TE or TM modes have a specific cut-off frequency, wave propagation is possible only above this frequency. A double- or multi-connected cross-section is necessary to propagate a TEM mode within a waveguide (multi-conductor transmission line, like TEM cell, stripline or open TEM waveguide). Each pair of two conductors creates a system for a possible specific TEM-mode propagation. For the example shown in Figure D.2, propagation of two separate TEM modes is possible. Each of these TEM modes has the same properties as the free-space TEM mode.

NOTE Each pair of conductors forms a TEM-mode transmission system. Inside a coaxial line the signal energy is transported via the TEM mode.

D.4 Wave propagation

D.4.1 General

Wave propagation describes the shape of the equiphase lines and surfaces of the field.

D.4.2 Spherical propagation

This type of propagation is the most common one in free-space far-field conditions. Normally it is caused by a point source like a single antenna. The field amplitude decreases with increasing distance to the source.

D.4.3 Plane wave propagation in free space

Very far away from an antenna, the wave front can be considered as planar. This kind of propagation will be observed within a parallel plate waveguide where the field amplitude is constant and independent of the distance to the source.

D.4.4 Velocity of propagation

The phase velocity of the TEM mode for propagation in free space and TEM waveguides is always equal to the speed of light c_0. It only depends on the permittivity ε and the permeability μ of the space.

D.5 Polarization

The electric field vector direction represents the polarization vector.

In general, the direction of the polarization vector changes with time. The curve traced out by the tip of the polarization vector, shown in Figure D.3 (see Clause D.8), defines the type of polarization.

From [8], the shape of the polarization curve can be calculated by the following procedure. The transverse electric field vector $\vec{E}_{\text{tr}}$ is given by Equation (D.5)

$$\vec{E}_{\text{tr}}(t) = \text{Re}\left\{\sum_{i=0}^{\infty} \underline{V}_i \cdot \vec{e}_{\text{tr},i} \cdot e^{\text{j}\omega t}\right\} \tag{D.5}$$

where

$\underline{V}_i$ is the voltage of the complex phasor of mode i;

$\vec{e}_{\text{tr},i}$ is the eigenvector of mode i.

The first term of the series represents the TEM mode, so a complex phasor can be written as Equation (D.6)

$$\underline{\vec{A}}_{\text{TEM}} = \underline{V}_1 \cdot \vec{e}_{\text{tr},i} = \underline{V}_{\text{TEM}} \cdot \vec{e}_{\text{tr,TEM}} \tag{D.6}$$

The phasor can be separated into its real and imaginary parts

$$\underline{\vec{A}}_{\text{TEM}} = \vec{a}_{\text{r}} + \text{j}\vec{a}_{\text{i}} \tag{D.7}$$

The vectors $\vec{a}_r$ and $\vec{a}_i$ define a fixed plane. In general the tip of vector $\vec{E}$ moves in an ellipse. If $\vec{a}_r$ and $\vec{a}_i$ are parallel, $\vec{E}$ moves on a fixed line; this case is called linearly polarized. Any individual modes are inherently linearly polarized. Only superposition with other modes results in circular polarization. The intentional TEM mode for testing purposes in TEM waveguides is usually linearly polarized.

D.6 Types of TEM waveguides

D.6.1 General

The simplest version of a TEM waveguide is a two-conductor transmission line as shown in Figure D.4 (see Clause D.8).

The complete transmission line can be described in terms of three physical sections.

a) Feed section: This is the measurement or test port where a signal generator or receiver is connected to the TEM waveguide.
b) TEM-waveguide section: Usually contains the test volume.
c) Termination section: Normally the termination represents an actual or equivalent resistor which is equal to the characteristic impedance of the transmission line (= TEM waveguide).

For most two-port TEM waveguides, the feed and termination sections are geometrically identical and therefore interchangeable. A coaxial connector is used at both ports. Some TEM waveguides are based on a balanced transmission-line system, in which case a balun transformer is needed.

Firstly, TEM waveguides can be classified into closed and open geometries. A TEM waveguide structure is called "closed" when one conductor fully surrounds the other conductor. In these cases, the outer conductor also acts as an electromagnetic shield.

Secondly, there are one-port, two-port, and four-port TEM waveguides (Figure D.5 to Figure D.11). This classification defines the termination of a TEM waveguide. Normally the TEM waveguide is used under impedance-matched termination conditions. The simplest way to match a two-port or a four-port TEM waveguide is to put a lumped termination equal to the characteristic impedance at one port. In this case, it is assumed that the TEM line geometry close to the ports (tapered section) is well designed for wide-band matching.

For a one-port TEM waveguide, the termination is made with distributed resistors or a combination of anechoic absorbers or both. TEM waveguides with this type of termination can be used up to several GHz with some geometries. For a two-port TEM waveguide, rather than a wide frequency range it has the advantage of allowing measurements of reflected and transmitted powers at either port.

Septum conductors can either be single or multiple wires connected in parallel, or single or multiple plates connected in parallel. For multiple-conductor systems, the excitation amplitude and phase can be intentionally changed to vary the dominant polarization within the test volume.

The septum can be installed either symmetrically or asymmetrically relative to the outer conductor. The advantage of an asymmetrical TEM waveguide is a larger test volume.

D.6.2 Open TEM waveguides (striplines, etc.)

A simple open TEM waveguide can be built using a plate installed over a conducting ground plane. A generator or receiver (typical impedance 50 Ω) is connected at one port, and the other port is matched to the transmission line characteristic impedance. A constant voltage/current distribution along the structure is achieved with proper impedance matching. This geometry is called an open two-port TEM waveguide.

The main disadvantage of open waveguides is energy lost to radiation. This unwanted radiation can cause interference to the test equipment system. Particularly for continuous-wave immunity testing, a shielded room for the open waveguide is absolutely necessary.

D.6.3 Closed TEM waveguides (TEM cells)

The main advantage of the closed TEM waveguide configurations is the inherent shielding. All immunity tests can be performed without generating any disturbance to the environment. Another advantage is that a closed TEM waveguide is an unbalanced system, so a balun is not needed. Lastly, in general a closed TEM waveguide has no low-frequency limit. For that reason, transient tests can be performed with closed TEM waveguides.

NOTE For a symmetrical-feed TEM waveguide, a low-frequency limitation is typically introduced by the balun.

D.7 Frequency limitations

The operation of a TEM waveguide is predicated on the assumption that the TEM mode has an identical field structure to that of a plane wave in free space over a defined portion of the cross-section of the cell. Therefore, using a TEM waveguide in emission measurements or immunity tests requires the propagation of the TEM mode over the usable frequency range.

For a given frequency within the operating range of the empty waveguide, the EM wave will encounter a cross-section of a dimension that will allow propagating modes other than TEM to be established. For a given non-TEM mode, the point along the TEM waveguide's length at which the mode can propagate is dependent on frequency, and moves back towards the feed point with increasing frequency. The lowest order non-TEM mode (typically TE_{10}) is able to propagate when one cross-sectional dimension of the waveguide exceeds one-half of the free-space wavelength at that frequency. Higher order modes are launched initially by mode conversion from the TEM mode. Energy conversion between two modes is caused by irregularities in the waveguide structure that can couple to both modes.

In practice, many open and closed TEM waveguides include some type of foam or ferrite anechoic absorbers to minimize or remove the higher order modes and non-propagating resonant field distributions. If installed in the proper locations relative to the modal field distribution, the TEM mode characteristics can be essentially preserved. Generally, with the proper combination of absorber loading and input/output conductor tapering, many TEM waveguides will operate in a TEM mode up to frequencies of several GHz or higher. Proper absorber placement is determined by the shapes of the input/output tapers and the test-volume section. The disadvantage for many TEM waveguides with absorber lining in the test volume section is that the field factor e_{0y} (see A.3.2.3.3) used in the emissions correlation algorithm can no longer be calculated analytically. This can lead to higher measurement uncertainties.

For any TEM waveguide with or without absorber, the valid frequency range shall be established using the methods described in this document (see 5.2.2).

For TEM waveguides without absorber, resonant frequencies depend on the geometry of the TEM waveguide. In a two-port TEM cell they occur between a certain cross-section of the feed section and the termination section, called the cut-off positions z_{C}. Each higher order mode can have a different cut-off position depending on the mode type. In between the feed and the cut-off position, the field mode is not able to propagate. A resonance occurs if the distance between the two cut-off positions is a multiple of one half wavelength. For symmetrical reasons, the resonant field will have a maximum or be zero in the middle of the cell at $z = z_{\mathrm{sym}}$. Further information about field homogeneity and resonant frequency is given in [22], [23], [24] and [50].

D.8 Figures for Annex D

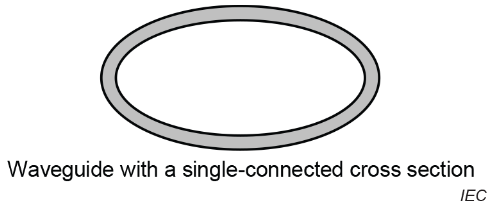


Figure D.1 – Simple waveguide (no TEM mode) (see D.3.3)

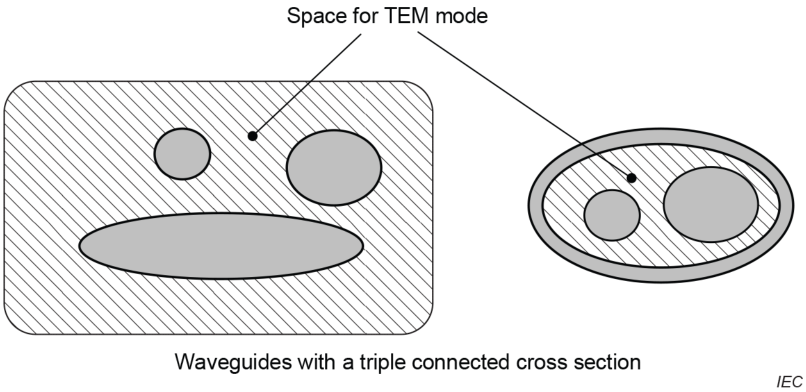


Figure D.2 – Example of waveguides supporting TEM-mode propagation (see D.3.3)

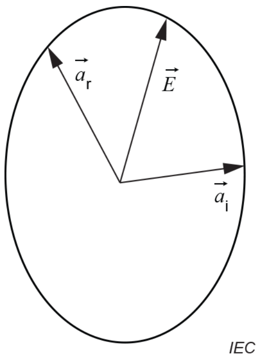


Figure D.3 – E-field polarization vector (see Clause D.5)

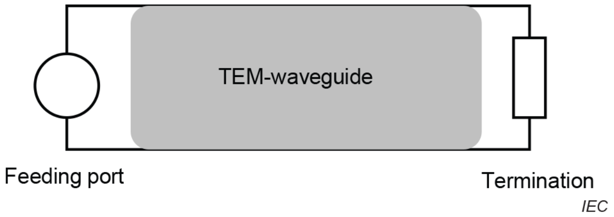


Figure D.4 – Simple transmission line model for TEM mode propagation (see D.6.1)

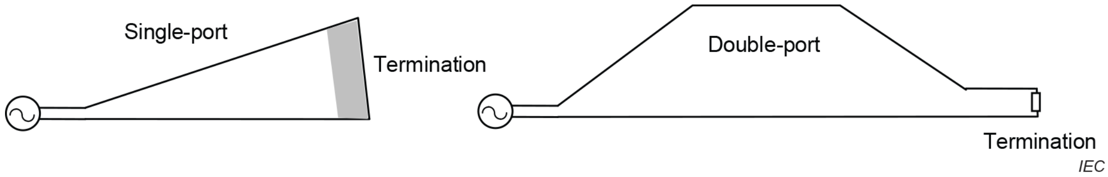


Figure D.5 – One- and two-port TEM waveguide concepts (see D.6.1)

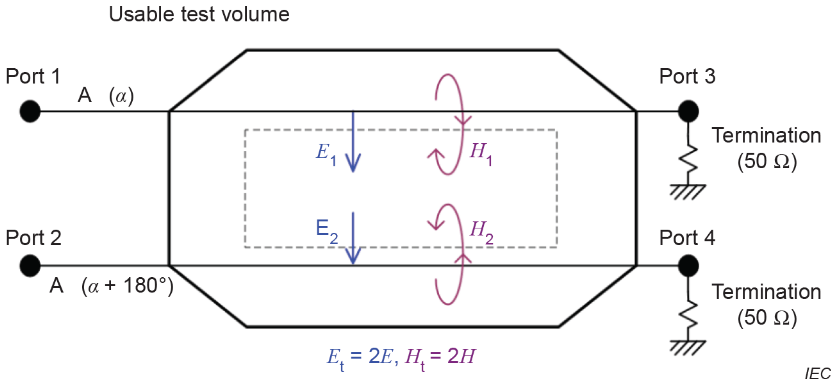
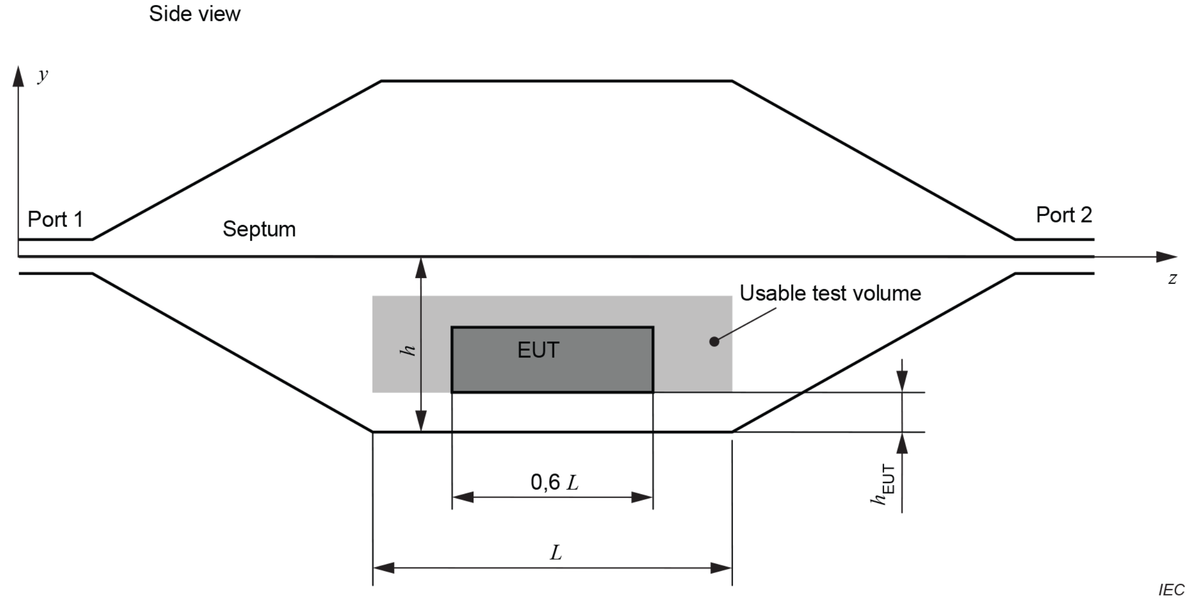
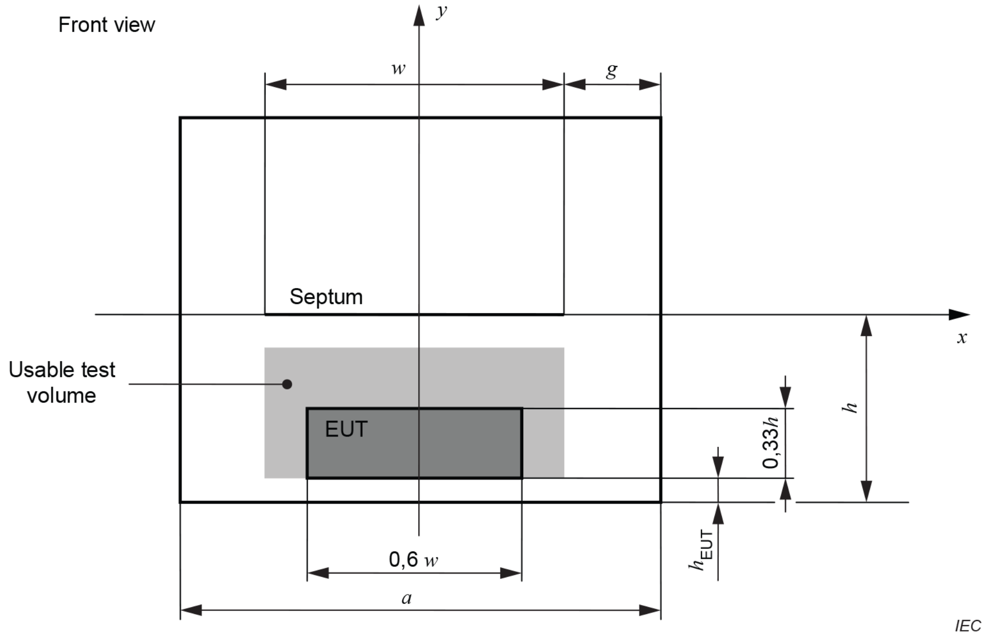


Figure D.6 – Operation of four-port TEM waveguides (see D.6.1)



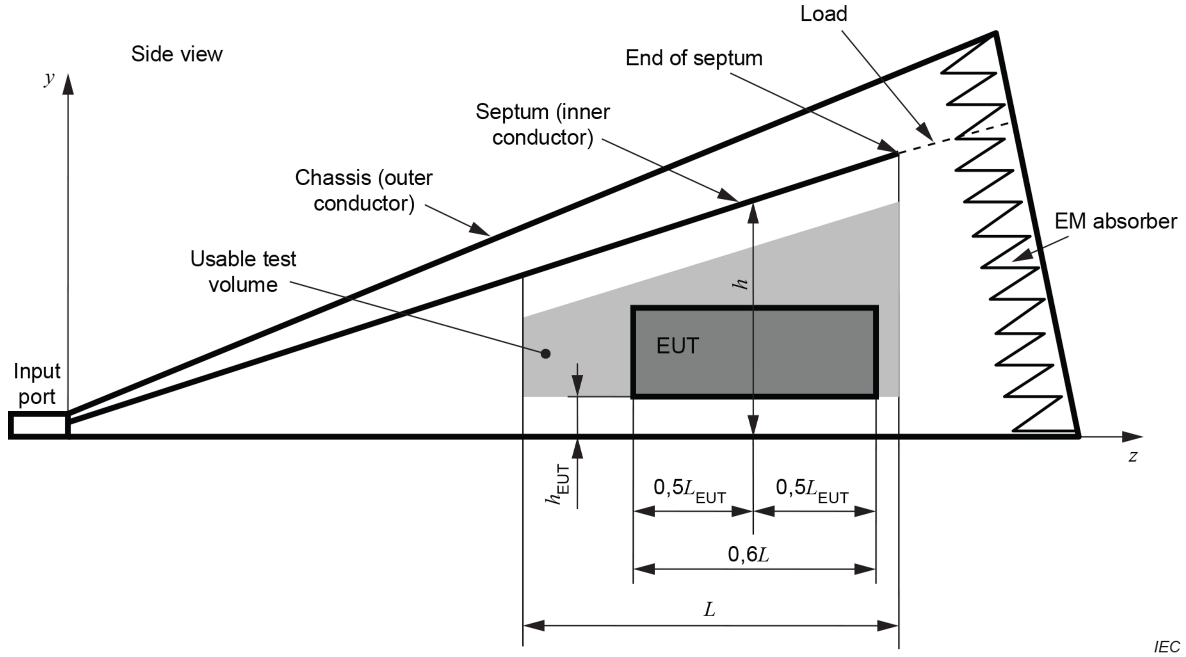
a) **Side view**



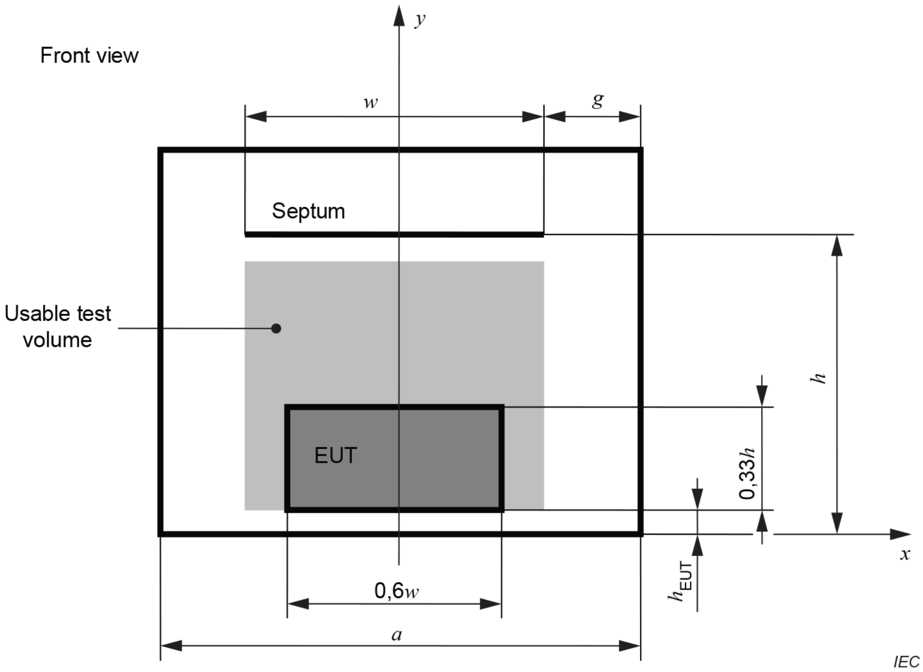
b) **Cross-section view**

NOTE h_{EUT} is the minimum distance between the EUT and each conductor or absorber of the waveguide.

Figure D.7 – Two-port TEM cell (symmetric septum) (see D.6.1 and D.6.3)



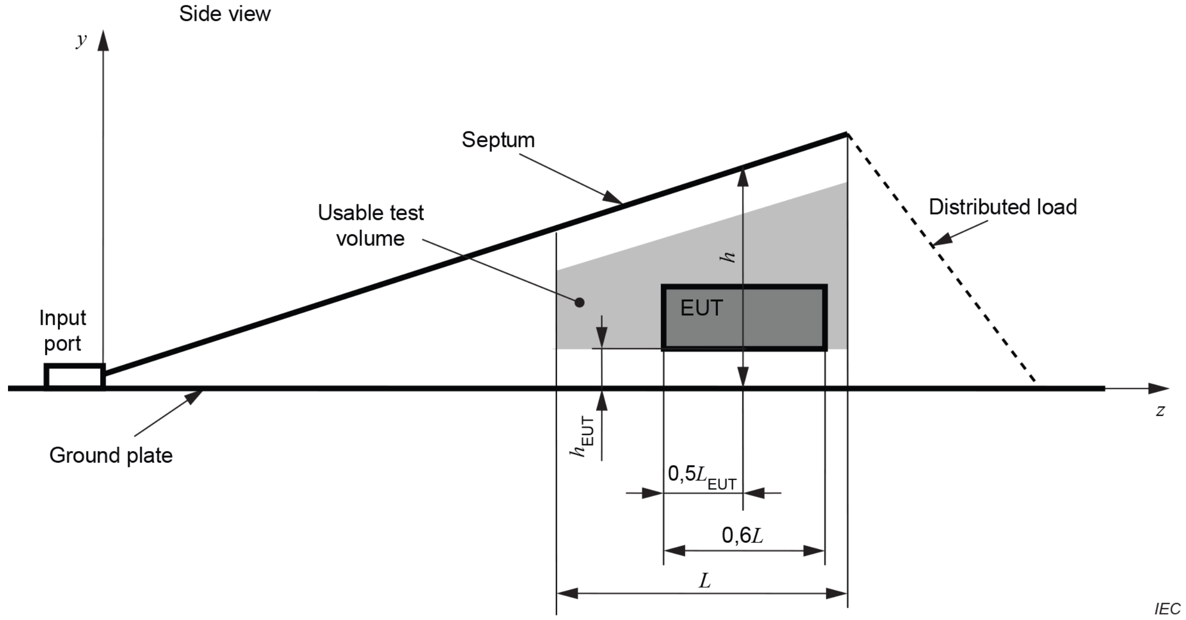
a) **Side view**



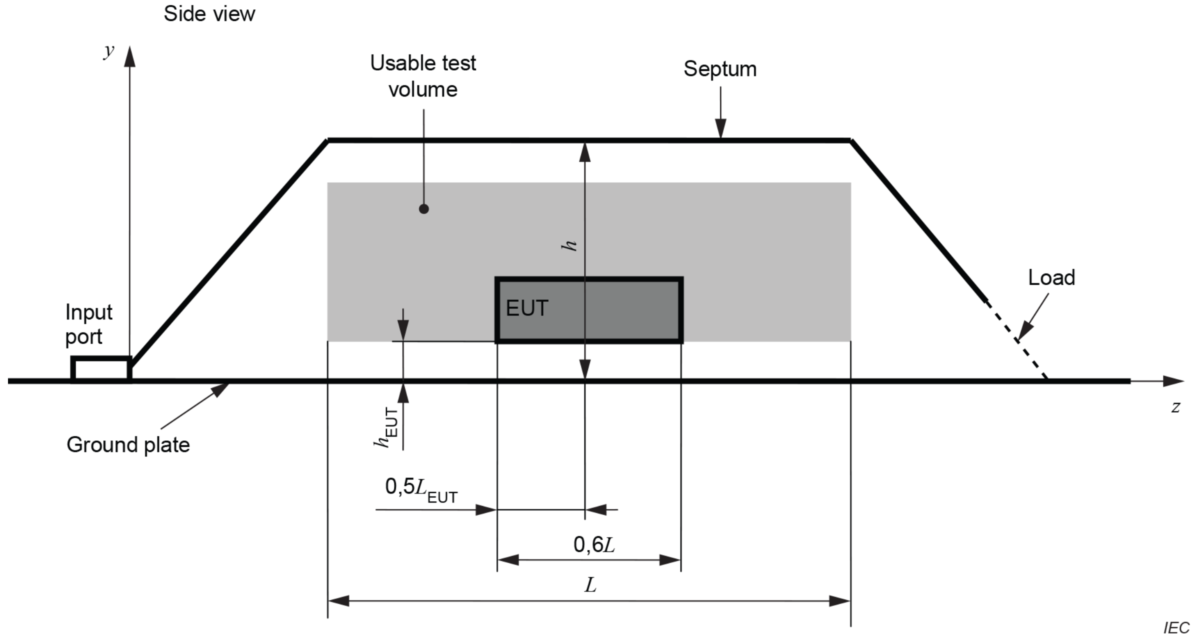
b) **Cross-section view**

NOTE h_{EUT} is the minimum distance between the EUT and each conductor or absorber of the waveguide.

Figure D.8 – One-port TEM cell (asymmetric septum) (see D.6.1 and D.6.3)



a) Side view (one-port)



NOTE A tri-plate stripline with centre-line side view like that of Figure D.7a) is obtained using the Figure D.9b) geometry and image theory.

b) Side view (basically similar to a two-port TEM waveguide, but some versions have a distributed load at the output port)