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The Transmission Of Electro-Magnetic Waves In Rectangular Waveguides

The waveguide is considered to be the most important transmission element for low loss transmission of electro-magnetic waves and signals from 1GHz upwards. At frequencies below 1GHz, coaxial cable can be more economically used for the transmission of broad band signals, however as the frequency increases the transmission losses play a larger and larger role. The article below takes a closer look at the transmission of electro-magnetic waves in waveguides.

1. Introduction

In principle, the transmission of high frequency signals should take place with as little loss as possible. For signals of up to 1GHz, this can be dealt with entirely by using modern, low loss coaxial cables. Above 1GHz, however, transmission losses play a larger and larger role, due to cable attenuation.

This disadvantage is often accepted for amateur radio use on grounds of cost. This means a high degree of attenuation in feeders to antennas (parabolic reflector, horn radiator, etc.) if the coaxial cable used is not designed for high frequencies.

For this reason, waveguides are predominantly used in commercial equipment for frequencies above 1GHz (e.g. radar and broad band directional radio), in order to achieve the lowest loss possible.

2. Wave propagation in waveguide

When using waveguides, you must take into account the fact that the cross sectional area and the shape determine the frequency response of waveguides. Mismatches between the waveguide input and output are particularly important, as are discontinuities, e.g. poor flange couplings. These can lead to reflections and to the formation of standing waves, and can make it increasingly difficult to predict the wave propagation pattern.

2.1. Significance of lower limiting frequency for waveguides

When signals are transmitted using waveguides, the frequency, the power of the signal being transmitted and the bandwidth, determine the shape and waveguide cross sections. Rectangular, round and ridge waveguides are of importance here.

So that we can understand wave propagation in waveguides, we must now intro-

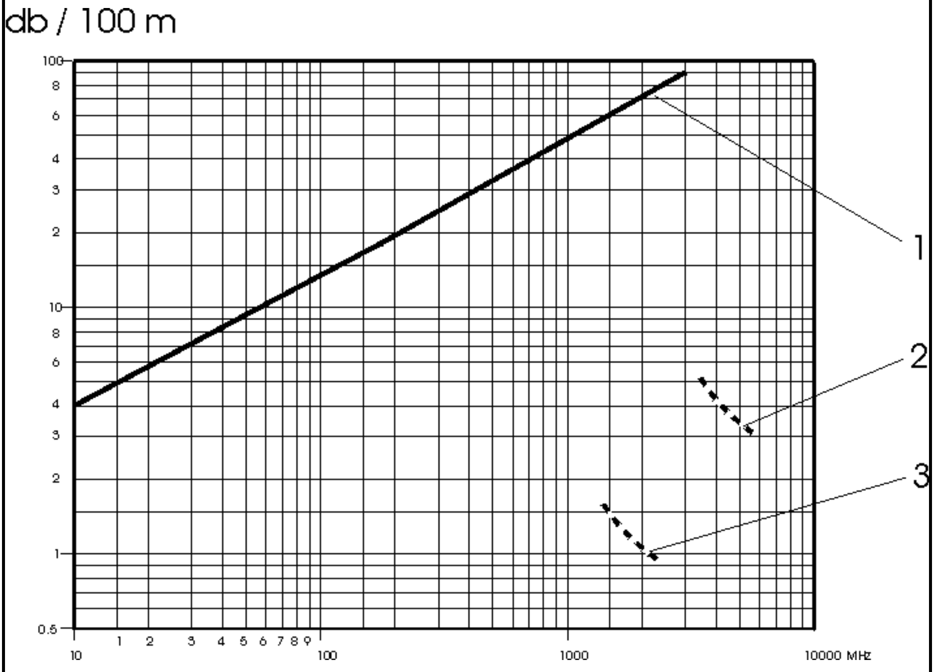

Fig. 1: Attenuation curve of coax cable in comparison to waveguides:
Curve 1: RG 55B/U 50-Ohm coax cable, material solid PE
Curve 2: Rectangular waveguide type 40 AL
Curve 3: Rectangular waveguide type 18 AL

duce a few simplifications, but these will nevertheless produce sufficiently accurate results.

- The dielectric material in the waveguide is always considered as being loss free, so that ε = 1 (e.g. air).
- Only Joules heat loss due to the skin effect occurs, reflection losses due to mismatches between the transmitter output and the waveguide do not amount to anything significant.

2.2. Wave propagation in rectangular waveguide

Fig. 2 shows the wave propagation in a rectangular waveguide.

The following assumptions are made in the analysis below. A linear polarised electro-magnetic wave acts on the waveguide, and the transmitted wave is polarised parallel to the smaller side wall b.

It is further assumed that the wave acting on the waveguide always has a magnetic, H field component, Hx and an electrical, E field component, Ey that are perpendicular to one another. This gives rise to a resulting directional vector, Sz, which makes the wave move into the waveguide and generate an interference field in its interior, depending on the frequency of the signal.

Let us assume that a linear polarised wave, parallel to side b, is acting on the aperture of the waveguide, with the frequency at the aperture being lower than

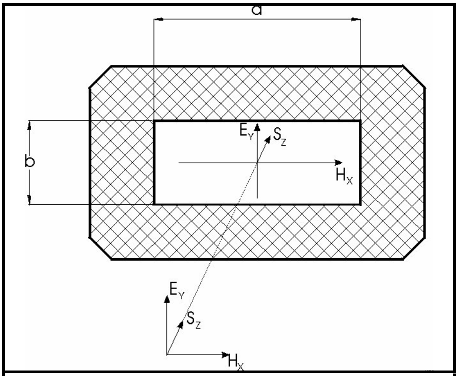

Fig. 2: Incidence of a wave into a rectangular waveguide. S_z = resultant directional vector, vertical to plane of drawing.

the limiting frequency, fg, of the waveguide. The current generated in the waveguide wall due to the low wavelength simply short circuits the electrical field. This field is called an attenuation type.

If we now slowly increase the frequency of the wave until the critical limiting frequency, fg, of the waveguide is reached, a stable electrical field wave is finally created, and a displacement current flows between the a sides. At this limiting frequency, the wavelength of the wave corresponds to double the length of the a side of the rectangular waveguide.

$$\lambda \leq 2a$$

From this frequency onwards, this electro-magnetic wave can enter the waveguide. The zig-zag reflection of the wave on the side walls of the waveguide now generate an interference field (Fig. 3).

Due to the reflection of the incident wave on the side walls of the waveguide, an interference field arises in the waveguide. There are now field areas in this interference field in which the fields of the incident and reflecting waves are added together. There are likewise field areas in which the amplitudes of the two waves cancel each other out. To make this easier to understand, the illustration in Fig. 3 looks at the special case in which λ_E=2a. In this case, this frequency, fo, derived from λ_E, is the limiting frequency, fg, explained above.

fo=fg in Fig. 3

It is also significant that a resulting new wavelength, λ_H, with the directional vector z, arises in the waveguide, due to the wave reflection of the incident wave.

The value of λ_H depends on the angle of

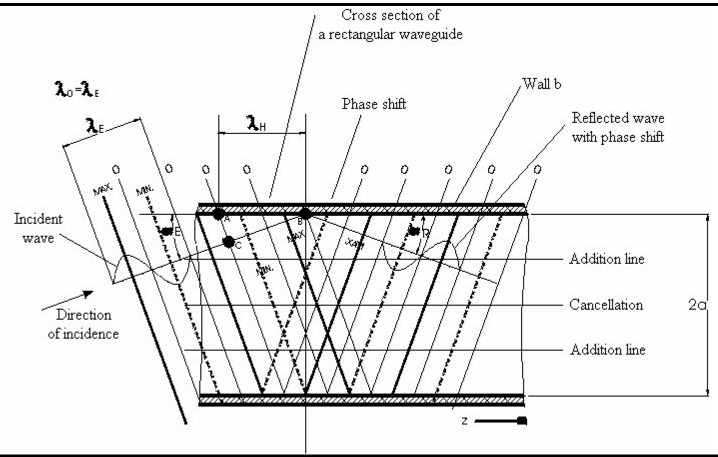

Fig. 3: Interference of a wave in waveguide.

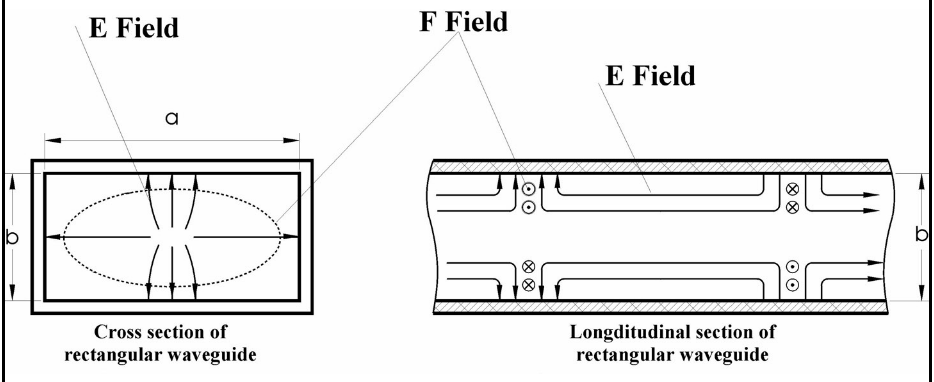

Fig. 4: TM wave in rectangular waveguide.

incidence, E, with which the incoming wave is reflected on the waveguide wall (see also Fig. 3).

Angle of incidence α_E=Angle of reflection α_R

The wave component, λ_H, can easily be derived from the geometry shown in Fig 3:

The section AC = λ_H

And the section BC = λ_0

$$\lambda_H = \frac{\lambda_0}{\cos\alpha_E}$$

The angle of reflection of the wave front is dependent on the frequency, fo, of the incident wave.

The new wave, λ_H arising from the interference field, with direction z, has an altered propagation speed, vg, compared with the wave, λ_0.

$$v_g = c \cdot \cos\alpha_E$$

$$c = \frac{1}{\mu_0 \cdot \varepsilon_0} = f_0 \cdot \lambda_0 [\lambda_0 = \lambda_E]$$

3.

Classification of wave types in waveguides

Dependent on the excitation of the incident wave entering the waveguide (polarisation of the wave), we distinguish between two basically different wave types:

Wave type 1 TM wave

Wave type 2 TE wave

We refer to a TM wave if the directional vectors of the electrical field lines are vertically to the direction of incidence of the incident wave (see Fig. 4). The resulting vector product, E x H, then gives an E field strength in the propagation direction of the wave, and we therefore refer to it as an E wave. This would be clearly visible if we split the waveguide in the longitudinal direction and examined the two resulting field components, E and H.

An example field pattern is shown in Fig. 4. The resulting H field lines are circular and vertical to the plane of propagation. The electrical fields are parallel to the

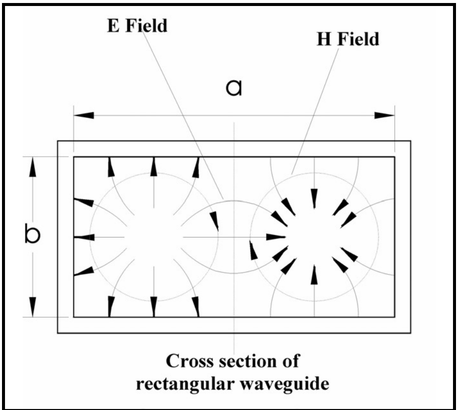

Fig. 5a: Field image of a TM_{21} wave in rectangular waveguide.

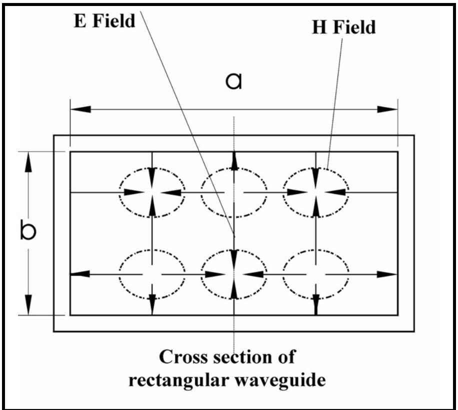

Fig. 5b: Field image of a TM_{32} wave in rectangular waveguide.

longitudinal axis of the waveguide. This means that the resulting E field strength causes an E wave to be propagated in the longitudinal direction of the waveguide. We can see the circular magnetic H field in the cross sectional representation in Fig. 4. By contrast, the electrical fields terminate at the internal walls of the waveguide.

However, in the middle of the cross section there is no conductor where the electrical E fields can terminate, they therefore bend round in direction z and thus determine the propagation direction of the E wave. This is called an E_{11} wave.

The following statements are thus valid for understanding wave propagation in waveguides:

- Magnetic H field lines are closed and run tangential to the waveguide walls.
- Electrical E field lines are either closed or terminate vertical to the inner walls of the waveguide.
- Electrical and magnetic field lines are always vertical to one another.

The following naming convention has been adopted and applies to both main groups H waves and E waves:

H waves TE_{mn} waves

E waves TM_{mn} waves

We can therefore determine the type of wave within the two main groups, the number of closed field areas of the H fields and/or the E fields in the cross section of the waveguide is counted (see Figs. 5a and 5b).

3.1. E waves

This does not pose any problems with the various TM waves, as can be seen in Figs. 6a and 6b.

The number of H fields is counted along side a (direction x) and along side b (direction y) of the waveguide.

In Fig. 5a we see two closed H fields along side a (direction x) and one row of H fields, in relation to side b (direction y).

This gives us:

$m = 2$

$n = 1$

Therefore were dealing with a TM_{21} wave here.

In Fig. 5b we observe three H fields along side a and two complete field areas lying on top of each other along side b. This gives a TM_{32} wave.

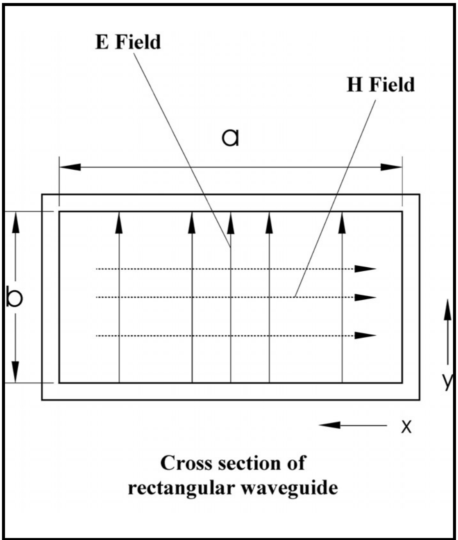

Fig. 6a: H_{10} wave in rectangular waveguide.

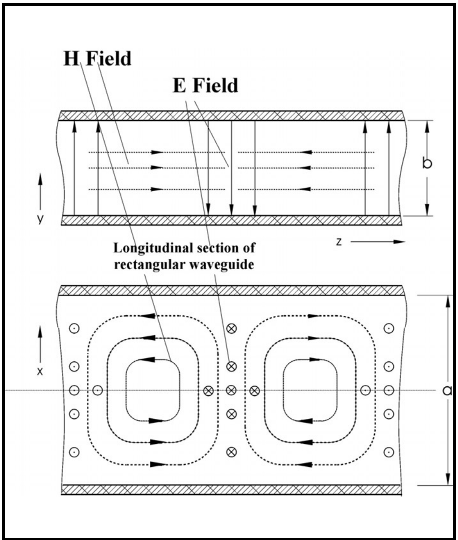

Fig. 6b : H_{10} wave in rectangular waveguide.

3.2. H waves

Lets go on to the H waves (TE waves). Figs. 6a and 6b show an H_{10} wave. It can be seen from Fig. 6b that the field lines of the H fields are orientated in direction z of the waveguide, and we can therefore refer unambiguously to an H wave. Figs. 7a and 7b give an example of an H_{20} wave, here two closed H fields are orientated in direction x, and shift into direction z with the changing polarity.

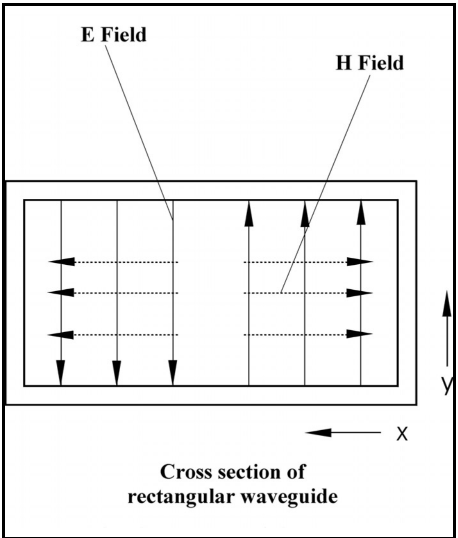

Fig. 7a : H_{20} wave in rectangular waveguide.

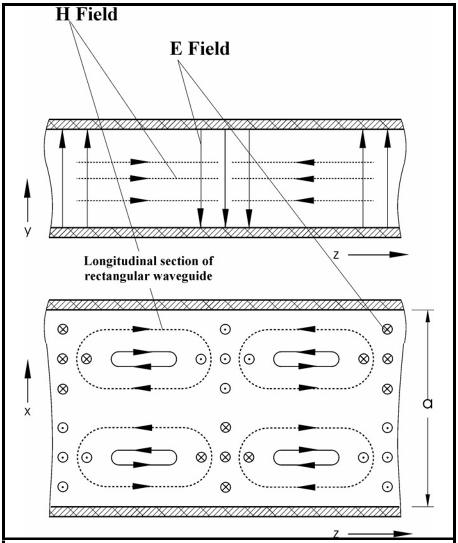

Fig. 7b : H_{20} wave in rectangular waveguide.

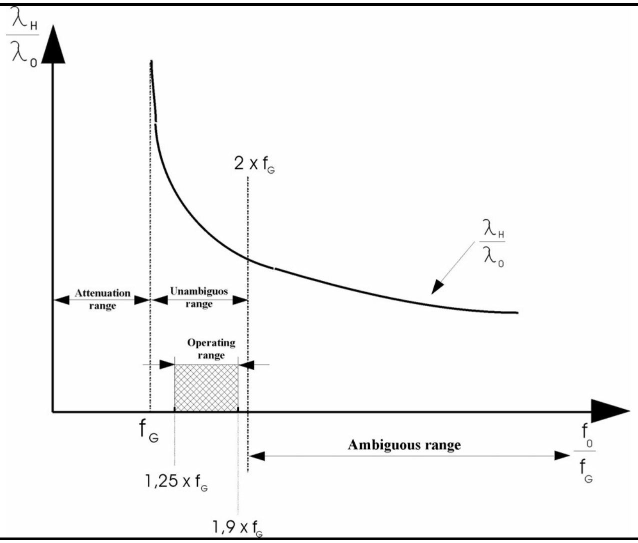

Fig. 8: Frequency and application ranges of rectangular waveguides.

4.

Wall currents in the waveguide

So far we have examined only the various field distributions of the magnetic H fields and the electrical E fields in the waveguide. For a comprehensive understanding of wave propagation in waveguides and of their construction, we must also consider the wall currents in the waveguide.

The occurrence of electrical wall currents on the surface of the internal walls of the waveguide can be explained by the fact that alternating magnetic alternating (tangential H fields) cause a surface current in a conductive body. Here the current flow is orientated vertically to the polarisation of the magnetic field and thus vertically to the concentric field lines of the H field. If we now look once again at the field distribution in the H_{10} wave (Fig. 6), we recognise that H_{10} wall currents can thus always be found in the vicinity of H field lines, with their directional vectors being orientated vertically to the circle of the concentric field lines.

In accordance with this definition, the complex wall currents can also be derived for any other wave types of E waves and H waves. What is of interest here is that the wall current generated penetrates only to a depth, δ, into the internal waveguide wall (skin effect). Thus, particularly in very high frequency applications (f>20GHz), the waveguides internal walls are often electro-plated with a layer of gold, silver or copper in order to obtain a high degree of conductivity for the waveguide surface.

5.

Phase velocity and frequency response in rectangular waveguides

For the transmission of high frequency waves in waveguides, the high degree of dependence on the frequency (in contrast to coax cables) must be taken into ac-

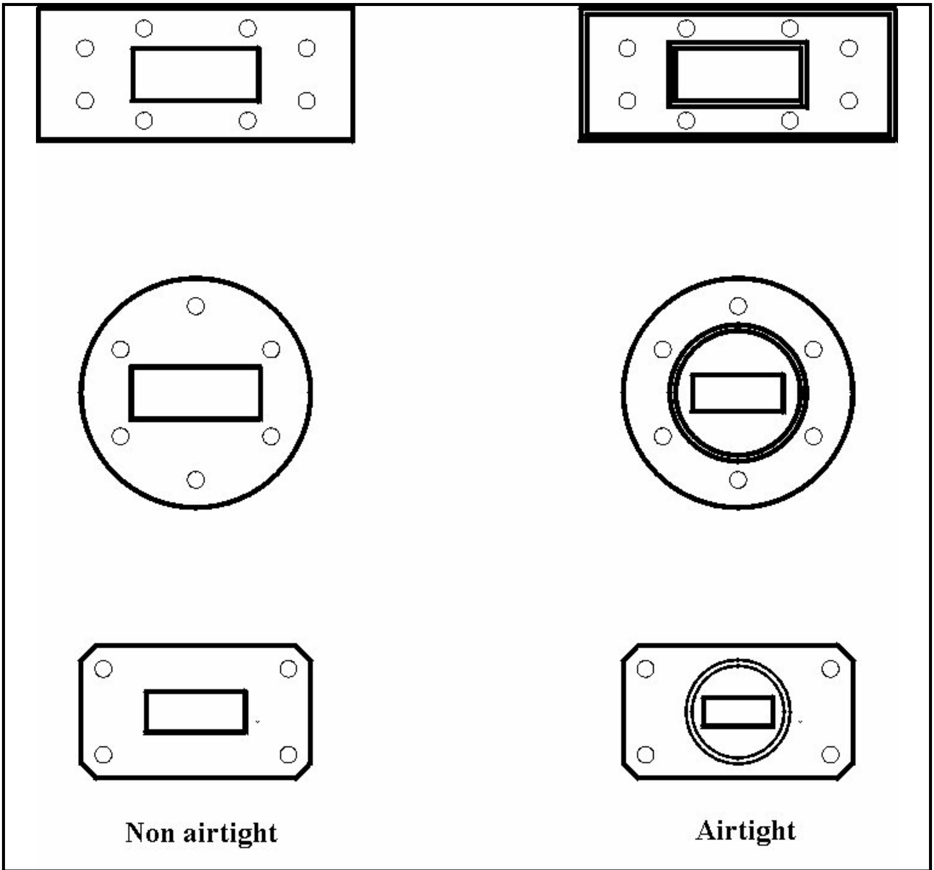

Fig. 9: Basic forms and constructions of waveguide flanges.

count. The signals fed into the waveguide display a phase velocity that varies with the frequency. The phase velocitys dependence shows itself, in particular, in the vicinity of the lower limiting frequency, fg. For broadband, high frequency transmission, this leads to a frequency dependent distortion of the signal in phase and amplitude. So an “unambiguous range” is defined with a specified upper and lower transmission frequency for the waveguide section. The lower frequency is set to exceed 1.25 x fg and the upper cut off frequency is set at < 19 x fg.

6.

Guide wave impedance in waveguides

The fact that waveguides display a high degree of dependence on the frequency has already been mentioned. This property must also be taken into account for the matching of waveguide sections to standard terminating impedances, e.g. for 50Ω power amplifier stages. By contrast to coax cable, which is matched to the transmitter through its constant characteristic impedance, complicated circumstances are present for waveguides, since E fields and H fields are transmitted. The peak values of these fields now determine the maximum transmitted rf output, P.

Note: The maximum transmittable continuous wave power and rf peak power are dependent on the cross sectional area, A, of the waveguide, and are also dependent on the breakdown field strength, which is dependent on the pressure, temperature and relative humidity.

For waveguides the wave impedance is introduced as a replacement for the characteristic impedance, defined as the quotient of the peak value of the electrical field, Ey, and the peak value of the magnetic field, Hx,. But its level is also dependent on the frequency of the signal, feeder wave.

Formulae:

$$Z_F = \frac{E_Y}{H_X} = \frac{Z_{F0}}{\sqrt{1-\left(\frac{\lambda_0}{2_a}\right)}}$$

Where wavelength of signal:

$$\lambda_0 = \frac{C_0}{f_0}$$

And characteristic wave impedance:

$$Z_{F0} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\Omega$$

7.

Coupling high frequency signals into rectangular waveguide

The rf input is fed to the waveguide either by means of a special waveguide flange connection on the transmitter output or through a broad band 50Ω coaxial connection, which then feeds the rf into a waveguide adapter. These adapters can be obtained for all types of cable and all standard coaxial plugs.

Finally, a few other basic waveguide flange constructions are illustrated in Fig. 9 in airtight and non-airtight versions.

8.

Literature

Strips and waveguides, Walter Janssen, Hüthig Verlag, 1992