Fast Fourier Transformation testing of structural return loss during extrusion of insulation

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The RF performance of a coaxial cable depends on its mechanical homogeneity. A criterion of this homogeneity, and therefore a criterion for the quality of the cable, is the return loss.

Cables with low return loss may affect signal transmission in the case of analogue techniques as well as in digital signal transmission procedures.

Normally, the return loss can only be measured when the coaxial cable has been made, even though failures to the cable have occurred at an early production stage. If the measured values of the return loss exceed the specified values the finished cable is both useless and worthless.

In the following article a new measuring procedure is described which allows cable manufacturers to predict return loss values during the extrusion of the insulation of a coaxial cable, by using Fast Fourier Transformation (FFT). With this new measuring procedure failure in production can be recognised and corrected at an early stage.

In this way the costs of cable production are reduced, cable quality is improved and, due to the reduction in cable scrap, a contribution to the environmental aspect is given.

The measuring procedure was developed and updated for the latest computer generation by Bedea's factory laboratories in cooperation with the Fachhochschule Gießen-Friedberg and the Institute of Technology TH-Darmstadt.

Coaxial cable production

Coaxial cable production can be divided into these four major steps:

- Manufacturing of the inner and outer conductors
- Extrusion of the insulation
- Screening
- Extrusion of the sheath.

During the production process the cable is run through an extrusion line or braiding machine, passing a lot of rotating devices which may cause periodical irregularities.

Experience has shown that most of the mechanical or structural irregularities that will cause reflections of a transmitted signal are subjected to the cable while extruding the insulation of the central conductor wire, or, they are already inherent to the central conductor wire.

Periodic failures may be inherent to the inner conductor, variations in the relative dielectric constant ε_r or variations in diameter of the insulation.

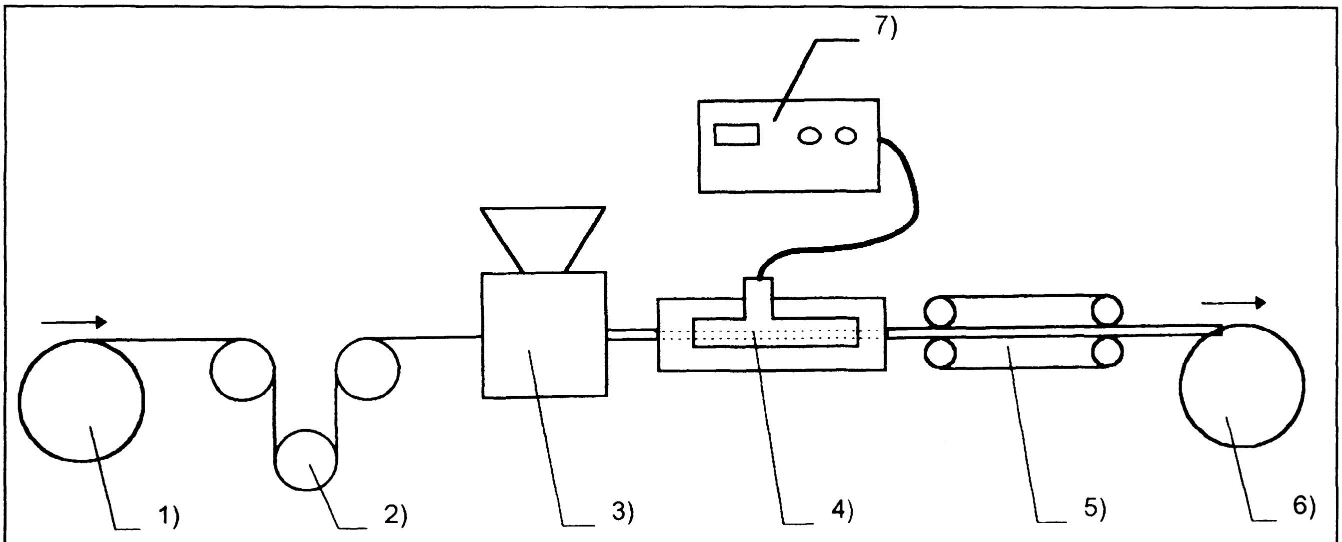

Figure 1. Schematic arrangement of an extrusion line.
1) Reel; 2) Tension device; 3) Extruder; 4) Cooling trough with capacitance measuring tube; 5) Caterpillar hauloff; 6) Takeup stand; 7) Capacitance control unit

Fundamental considerations

The characteristic impedance Z of a coaxial cable is given by:

$$Z = \frac{60}{\sqrt{\varepsilon_r}} \cdot ln\left(\frac{D}{d}\right) \; [\Omega] \qquad \ldots (1)$$

where

ε_r is the relative dielectric constant of the insulation material,

D is the diameter of the insulation,

d is the diameter of the inner conductor.

The capacitance C' per unit length is given by:

$$C' = 55{,}6 \cdot \varepsilon_r : ln\left(\frac{D}{d}\right) \; [\mathrm{pF/m}] \qquad \ldots (2)$$

The relation between the characteristic impedance Z and the capacitance C' is given by:

$$Z = \frac{\sqrt{\varepsilon_r}}{C' \cdot c_0} \qquad \ldots (3)$$

where,

c_0 is the velocity of light in a vacuum.

Reflection coefficient

An RF signal that is travelling through a transmission line with the nominal characteristic impedance Z_n will be reflected on any point i of this line where it meets an irregularity with a deviation from the nominal characteristic impedance Z_n.

The magnitude of the reflection at this point of irregularity is designated by the reflection coefficient r_i of a single reflection which is given by:

$$\underline{r}_i = \frac{\underline{Z}_L - Z_n}{\underline{Z}_L + Z_n} \qquad \ldots (4)$$

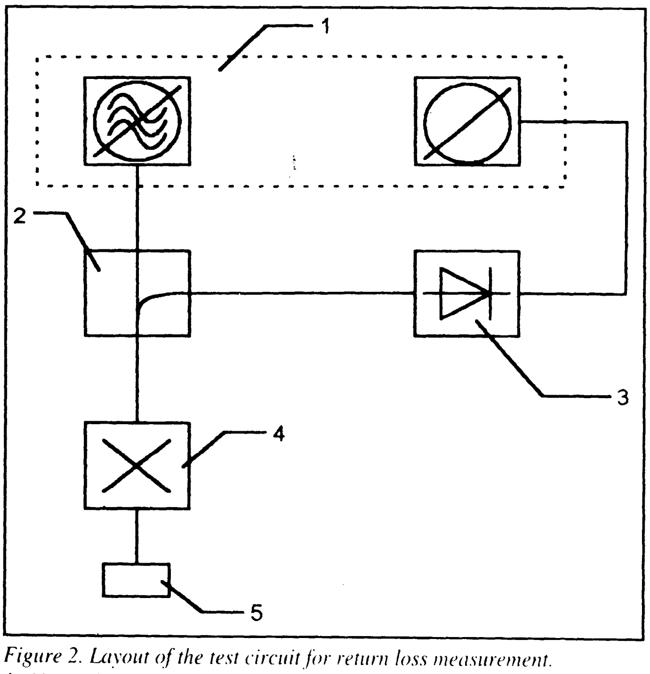

Figure 2. Layout of the test circuit for return loss measurement.
1) Network analyser; 2) Bridge; 3) Demodulator; 4) Cable under test; 5) Termination load

where,

Z_n is the characteristic impedance of the cable,

$\underline{Z}_L$ is the characteristic impedance at the point of irregularity.

The reflection coefficient r_i of a cable is "1" at an open end, "-1" at a shortened end and zero in the case of matching.

For standard applications, such as CATV networks, random or stochastic distributed irregularities over the cable length will not disturb signal transmission if the reflection coefficient r_i of a single reflection point is <0,01, respectively >40 dB. The maximum permissible values of a single reflection r_i are given in the detailed specification of a cable.

The total input reflection factor R at the input of the cable is the sum of the single reflections r_i.

If the irregularities of the cable are of a periodic distance l_0, the reflected signal and with that the total input reflection factor R at the input end of the cable will be a maximum at the resonance frequency f_r, which is obtained, to:

$$f_r = \frac{c_0 \cdot v_K}{2 \cdot l_0}, \qquad \ldots (5a)$$

$$= \frac{c_0}{2 \cdot l_0 \cdot \sqrt{\varepsilon_r}} \qquad \ldots (5b)$$

where,

c_0 is the propagation velocity in free space,

v_k is the velocity ratio,

ε_r is the relative dielectric permittivity of the insulation material.

It should be noted that the wave length λ of the resonance frequency f_r is $2\,l_0$.

Return loss

The input impedance of a coaxial RF cable at any frequency is a function of the variation of the local characteristic impedance distributed over the cable length.

Variations of the characteristic impedance may be caused by irregularities subjected to the cable during production.

In the case of periodic irregularities over the cable length the input impedance may differ considerably from the mean characteristic impedance at high frequencies.

The return loss a_r is a measure of the deviation from the mean characteristic impedance of a cable in the frequency domain and is the most important quality criterion of an RF coaxial cable.

The return loss a_r is defined as:

$$a_r = 20 \cdot \log\,(u_i / u_r), \quad \text{in dB} \qquad \ldots (6a)$$

$$= 20 \cdot \log\,(1/\underline{R}) \quad \text{in dB} \qquad \ldots (6b)$$

where,

u_i is the magnitude of the incident wave with reference to the impedance Z_n,

u_r is the magnitude of the reflected wave with the cable terminated with the impedance Z_n,

Z_n is the nominal characteristic impedance of the cable,

$\underline{R}$ is the reflection coefficient.

The return loss a_r is related to the total input reflection coefficient, $\underline{R}$, by:

$$\underline{R} = (u_r / u_i) \quad \ldots (7a)$$

$$= 10^{-(a_r / 20)} \quad \ldots (7b)$$

It is indirectly related to the standing wave ratio, s, by:

$$s = \frac{(1+R)}{(1-R)} \quad \ldots (8)$$

The procedure for measuring the return loss a_r on finished cables is given in the International Standard IEC 1196-1:1995, subclause 11.12.

Mathematical equivalent of a cable with irregularities

For the mathematical description of a coaxial cable with periodic irregularities, the equivalent circuit of such a cable normally uses the complex conductance $\underline{Y}$, connected in parallel to the characteristic impedance Z_n.

For better understanding we use a two port device as an equivalent circuit where the periodic irregularities are depicted as small parallel capacitors connected parallel to the nominal cable impedance Z_n at the distance l_0, assuming that the physical length of each disturbance is small.

The resulting characteristic impedance Z_L of the parallel circuit of the nominal cable impedance Z_n and the deviation ΔC from the nominal capacitance C' of the cable at one part of the line with the distance l_0 according to Figure 3 is given by:

$$\underline{Z}_L = \frac{1}{\frac{1}{Z_n} + j\omega \cdot \Delta C} \quad \ldots (9)$$

where,

ΔC is the deviation from the nominal capacitance of the cable.

ω is the angular frequency which is $2\pi f$.

With equation (9) inserted in equation (4) the single reflection factor $\underline{r}_i$ results in:

$$\underline{r}_i = \frac{\omega \cdot \Delta C \cdot Z_n}{\sqrt{4 + (\omega \cdot \Delta C \cdot Z_n)^2}} \quad \ldots (10a)$$

The expression $(\omega \cdot \Delta C \cdot Z)^2$ is small to the factor 4 in equation (10a) because of the small capacitance deviation ΔC and can therefore be neglected. With that simplification the single reflection coefficient $\underline{r}_i$ is given to:

$$\underline{r}_i = \pi \cdot f \cdot \Delta C \cdot Z_n \quad \ldots (10b)$$

The transformation of one single reflection of the cable's input with attention to attenuation is given by:

$$\underline{r}_{(l)} = \underline{r}_i \cdot e^{-2 \cdot \gamma \cdot l} \quad \ldots (11)$$

with the propagation constant

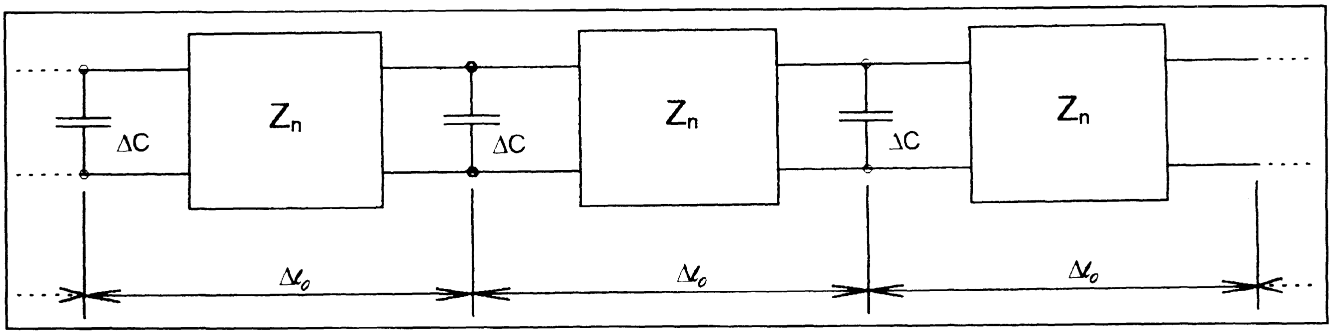

Figure 3. Equivalent circuit of a periodically disturbed coaxial line

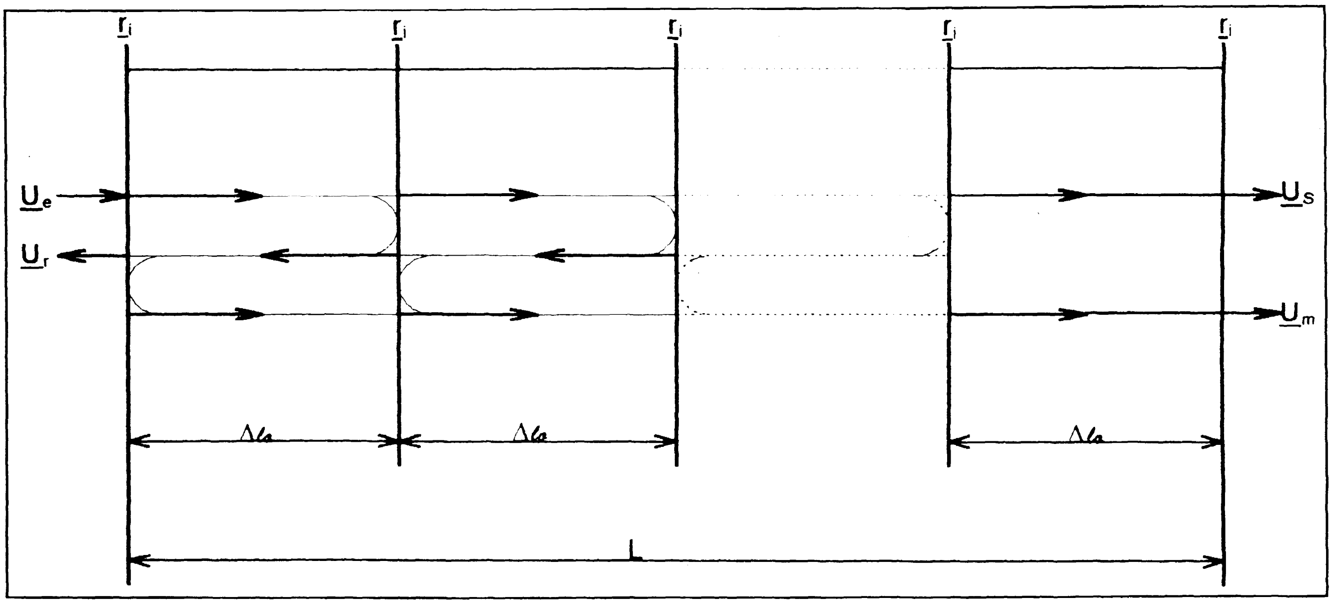

Figure 4. Schematic arrangement of periodic reflections

$$\gamma = \alpha + j\beta \qquad \ldots (12)$$

where,

l is the distance of the single reflection from the input of the cable,

α is the attenuation contact,

β is the phase constant.

For calculation of the return loss it is necessary to calculate the total input reflection factor $\underline{R}$ first.

The total input reflection factor $\underline{R}$ is the sum of the single reflection coefficients r_i, with attention to two times the attenuation of the length l_0 respectively n times the length l_0 at the nt. single reflection r_i.

The total input reflection factor $\underline{R}$ is obtained by:

$$\underline{R} = r_i \cdot \frac{1 - e^{-2 \cdot \gamma \cdot l_0 \cdot (n+1)}}{1 - e^{-2 \cdot \gamma \cdot l_0}} \qquad \ldots (13)$$

where,

n is the number of irregularities.

The total investigated cable length L is given by the number of irregularities multiplied by the distance of the irregularities l_0:

$$L = n \cdot l_0 \qquad \ldots (14)$$

In the case of resonance the phase constant β which is given by:

$$\beta = (2 \cdot \pi) / l_0 \qquad \ldots (15)$$

means that β becomes a multiple integer of two times π, which means |β| is 1.

With this simplification and with equation (14) the input reflection factor $\underline{R}$ results in:

$$R = \underline{r}_i \cdot \frac{1 - e^{-2\,\alpha(L + l_0)}}{1 - e^{-2 \cdot \alpha \cdot l_0}} \qquad \ldots (16)$$

where R is no longer a complex number.

With equation (16) inserted in equation (6b) and with equation (10b) the return loss a_r is obtained by:

$$a_r = -20 \cdot log \left| \pi \cdot f \cdot \Delta C' \cdot Z_n \cdot \frac{1 - e^{-2\,\alpha \cdot (L + l_0)}}{1 - e^{-2 \cdot \alpha \cdot l_0}} \right| \qquad \ldots (17a)$$

$$a_r \approx -20 \cdot log \left| \pi \cdot f \cdot \Delta C' \cdot Z_n \cdot \frac{1}{1 - e^{-2 \cdot \alpha \cdot l_0}} \right| \qquad \ldots (17b)$$

assuming that $L >> l_0$.

With the measure of the capacitance variation $\Delta C'$ related to discrete distances l_0, the return loss a_r can be calculated using equations (17a) and (17b).

Fast Fourier Transformation (FFT)

The Fourier Transformation (FT) is a mathematical procedure that is used to analyse a given signal into its sinusoidal and its periodical parts.

The Fast Fourier Transformation (FFT) is a special variation of this procedure and its suitable for fast computer calculations. The number of the calculated discrete spectral lines is a power of two. We use a 1,024 (2,048) line FFT.

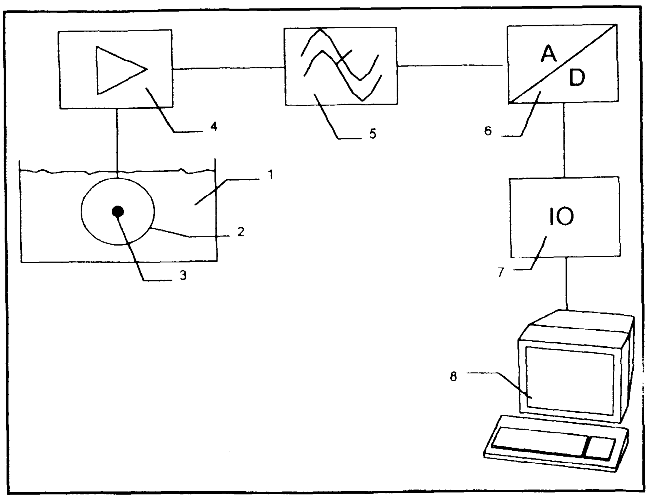

Figure 5. Block diagram of the measuring setup.
1) Cooling trough; 2) Capacitance measuring tube; 3) Insulated conductor; 4) Amplifier; 5) Anti-aliasing filter; 6) Analogue digital converter; 7) Input/output card (multitasking); 8) Personal computer

Measuring system

The measuring system consists of the capacitance measuring device, the anti-aliasing filter, the A/D converter, the multitasking card and the computer.

During extrusion of the insulation of the central conductor, the insulated conductor is running through the tube of a capacitance measuring device which is mounted in the cooling trough of the extrusion line, and the deviation from the nominal capacitance is measured as an analogue signal.

Measuring of capacitance of an insulated core is well known in the cable industry and the devices of many suppliers may be used.

To increase the upper frequency limit which can be investigated, a short measuring electrode should be used [see equation (5a)]. With an active electrode, part of 0.05 m, the upper frequency limit of the measuring system is 2.4 GHz.

To avoid misinterpretation, the analogue capacitance signal is filtered by an anti-aliasing filter with a high slope steepness and the fed to an A/D converter which transforms the analogue signal into digital values. This digitised signal is then analysed from the computer by FFT.

The A/D converter is combined with a multitasking card with its own microprocessor on board, through which four channels can be observed and simultaneously calculated.

The sampling rate of the A/D converter depends on the velocity v_L of the extrusion line and the shortest detectable distance of irregularities l_{0min} which is the length of the active part of the capacitance measuring tube.

The highest frequency f_{FFTmax} of spectral lines we obtain from the FFT is:

$$f_{FFTmax} = \frac{V_L}{l_{0min}} \qquad \ldots (18)$$

To fulfil the Shannon theorem, the sample rate is at least two times the highest frequency f_{FFTmax} of spectral lines.

The multitasking card collects arrays of 1,024 (2,048) values which are then fed "blockwise" to the computer, where the FFT is achieved and the return loss is calculated [see equation (17)].

The capacitance values C' versus time and the calculated values of the return loss a_r versus frequency are displayed on a monitor and may be recorded if desired. If the calculated values overshoot the specified limits, an alarm may be set off.

Although the system is designed to test return loss, stochastic distributed irregularities may be observed.

Depending on the "FFT-window" used, as well as on the magnitude of a single nonperiodical irregularity, the "noisefloor" of the FFT-signal will increase.

Magnitude and distance of stochastic distributed single reflections $\underline{r}_i$ of a finished cable may be measured, using a Time Domain Reflectometer (TDR).

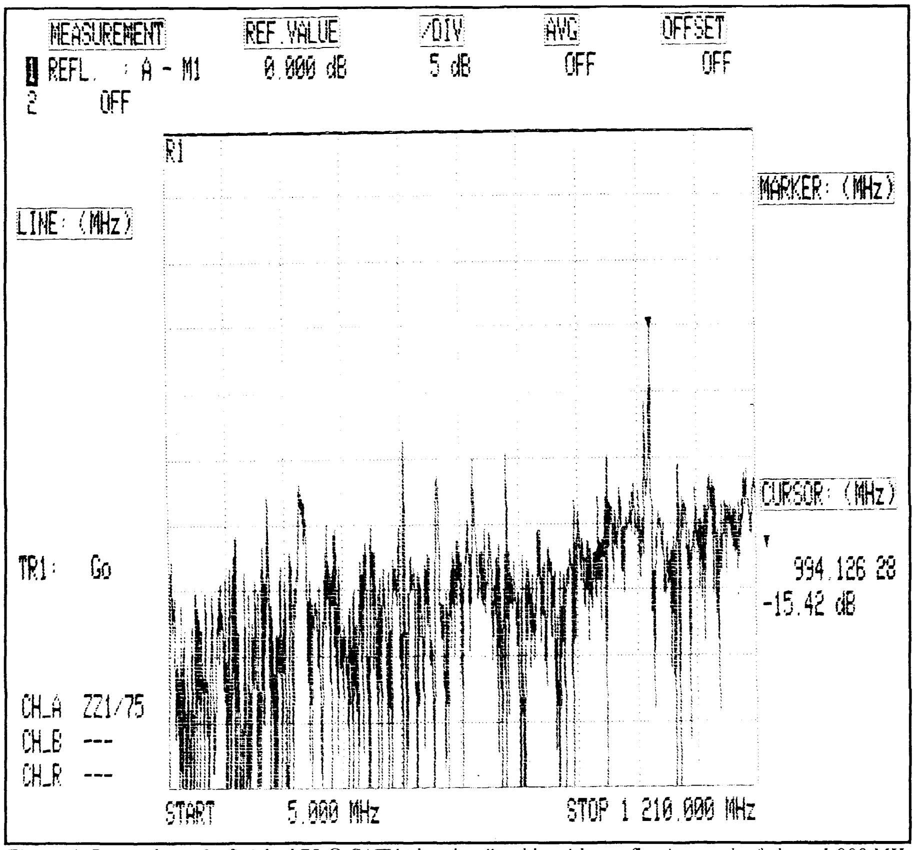

Figure 6. Return loss of a finished 75 Ω CATV "bamboo" cable with a reflection peak of about 1,000 MHz

Accuracy of the system

A good opportunity to check the measuring system is during the production of "bamboo" cables where the insulation consists of plastic slices and air; periodical irregularities are given by the slices of such a cable.

Figure 6 shows the return loss of a finished 75 Ω CATV "bamboo" cable with a reflection peak at about 1,000 MHz, corresponding to a distance l_0 of 132 mm which is eight times the distance of the single slices of 16.5 mm.

The application of this cable in the CATV field is specified up to 960 MHz so that during production eight slices may be extruded at a time.

The resulting relative dielectric constant e_r of the insulation material and the air of this cable is 1.136.

Observations over more than five years came to deviations between predicted and measured return loss on the finished cable with 3 dB on all types of the investigated cables, related to the measured peaks.

Depending on the cable's attenuation, which increases with increasing frequency, and depending on the number of periodic irregularities, the measure of return loss can be achieved only on a limited cable length.

Measuring of the return loss on the delivery length of a cable of about 1,000 m or more gives only information on the return loss from cable's ends.

The measuring system described gives full information about the quality of a cable over the whole cable length.

Although the procedure introduced deals with coaxial cables, it may also be applied to the insulation of cores of symmetrical cables, in order to achieve high quality.

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