Translation

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A SIMPLE METHOD FOR MEASURING THE ATTENUATION CONSTANT OF WAVEGUIDES

by

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1. Introduction

The problem of investigating the usability of silver conductive lacquers in the microwave region has arisen. The characteristic magnitude by which such a preparation should be judged is - from the physical point of view - the specific conductivity. In practical application, on the other hand, it is the losses of structural elements treated with these lacquers that is of interest. In addition to the geometry of the structural elements and the specific conductivity, the surface condition of the lacquers is largely responsible for the losses because of the slight skin thickness at high frequencies. It therefore appears appropriate for a practical comparison not to use the conductivity of the lacquers but rather the losses of a simple microwave structural element, e.g., the losses of a rectangular waveguide whose inside walls

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are painted with the conductive lacquer to be tested. An appropriate resonator measuring procedure is described in the following article.

II. Measuring Setup

The principal measuring setup, which is basically a typical reflectometer system, is shown in Fig. 1. The waveguide to be tested is supplemented by adding a shorting plunger and a variable shutter to a resonator. The variable shutter is operated by a metal pin that is movable along its longitudinal axis (Fig. 2a). The image on the (indirect) double-beam oscillograph reproduces the output reflected by the analyzer (resonator); the other image indicates the frequency measurement.

The measurements described here were made in the so-called X-band (8.2 - 12.4 GHz) with WR-90 waveguides. All references to apparatus in this article pertain to this frequency range.

If the attenuation of the analyzer at frequency ν_0 - the corresponding waveguide wavelength being Λ_0 - is to be determined, the distance between the shorting plunger and coupling pin is selected such that it is an integral multiple of half the waveguide wavelength Λ_0. If we now change the penetration depth of the coupling pin from small values to increasingly greater ones, we note that the reflection coefficient r of the analyzer disappears at two specific frequencies. in the immediate vicinity of ν_0 (Fig. 3). As will be shown, the losses and - after subtraction of the losses of the shorting plunger and the coupling pin - the attenuation of the analyzer can be determined from the difference between these two frequencies. A common way of separating these losses from one another consists of repeating the measurements for various resonator lengths. The losses of the shorting plunger and the shutter remain constant, while the attenuation losses change with the resonator length.

The advantages of the suggested measuring method over other procedures (cf. Ginzton, Ref. 1, Wind-Rapaport, Ref. 2,) are:

1. The shorting plunger does not need to be precision-adjusted during the measurement.

In measuring conductive silver, only a shorting plunger with a larger air gap can be used because of the unavoidable variation in thickness of the conductive silver paint. The shorting plunger losses thus created can now be reduced and compared with one another at the individual plunger positions if the remaining air gap is filled with conductive lacquer. This is possible only, however, if the position of the plunger does not have to be changed again.

2. Since the necessary measurement data can be obtained only with disappearing reflectivity coefficients, i.e., a "null method" is used, neither the characteristic curve and its frequency dependence, nor the output variations of the MW transmitter have an effect on the measurement results.

III. Measuring Method Theory

The measuring method, and the effect (Fig. 3) on which it is based, can be explained by three well known facts:

1. A conductive, longitudinally movable pin has the practical effect in a waveguide of a reactive, broadly variable transverse conductive $iYq = 1/iXq$ (Fig. 2).
In the first approximation, it can be assumed that the series resistances $-iXL$ and loss resistance R are negligibly small in the equivalent-circuit diagram (cf., for example, Meinke-Gundlach, Ref. 3, p. 412). As will be shown later, corrections are easily made.

2. The transformation of a complex conductance into the wave impedance G_O of the connected circuit is equivalent to fitting to nonreflectivity. With a reactive, variable transverse conductance iYq - for which a conductive pin can be used in waveguide systems according to 1) - all conductances of the form $G_O - iYq$ can be transformed into the wave impedance G_O. In the Smith diagram, the locus curve $G_O - iYq$ (with variable $Yq \gtreqless 0$) is represented as a circle (circle K in Fig. 4):

$$\left(x-\frac{1}{2}\right)^2+y^2=\left(\frac{1}{2}\right)^2. \qquad (1)$$

3. The locus curve of the input conductance of a short-circuited loss circuit of length 1 spirals around the source in the Smith diagram as a function of frequency or wave-length (Fig. 5).
This spiral-like curve tightens around the source of the Smith diagram with increasing frequency or approaches the edge, depending on whether the attenuation of the waveguide increases or decreases with rising frequency.
At certain frequencies $\nu_O^{(k)}$, the conductance of the

short-circuited circuit is real and greater than G_0; this occurs when length l is an integral multiple of half the waveguide wavelength $\Lambda_0^{(k)}$ belonging to $\nu_0^{(k)}$:

$$l = k \frac{\Lambda_0^{(k)}}{2} \quad \text{mit } k = 1, 2, \ldots \qquad (2)$$

In the Smith diagram, these points are on the abscissa for

$$x = |\varrho_0| \, e^{-2\alpha l}. \qquad (3)$$

where ρ_0 is the reflectivity coefficient of the shorting plunger and α the attenuation value of the waveguide. Both ρ_0 and α are generally only slightly dependent on frequency. Therefore, the spiral-like curve for this frequency region $\nu_0^{(k)} = \nu_0$ can be approximated by a circle:

$$x^2 + y^2 = |\varrho_0(\nu_0)|^2 \cdot e^{-4\alpha(\nu_0) l} \qquad (4)$$

From points 1) to 3), it can be concluded (Fig. 5) that, as stated earlier, a lossy, short-circuited circuit through a thin, variable shutter can be coupled without reflectivity to another circuit at two frequencies ν' ν'' in certain frequency regions ν_0. In particular, it follows from Eqs. (1) and (4) for angles ψ' or ψ'' (see Fig.5) that

$$\cos \psi = |\varrho_0| \, e^{-2\alpha l} \qquad (5)$$

with $\psi = \psi' = \psi''$.

It can be demonstrated (which, however will not be done in further detail here because of space limitations that the transverse resistance iXq, which is required for fitting, has the value

$$\frac{iX_Q}{Z_0} = \pm i \frac{\operatorname{tg} \psi}{2} \tag{6}$$

where $Z_0 = 1/G_0$ is the characteristic impedance of the circuit. Angles ψ', ψ'', on the other hand, are determined by lenth l of the analyzer and waveguide wavelengths Λ', Λ'':

$$\begin{aligned} \psi' &= 2\left(\frac{2\pi l}{\Lambda'} - k\pi\right) \\ \psi'' &= -2\left(\frac{2\pi l}{\Lambda''} - k\pi\right) \end{aligned} \tag{7}$$

(k follows from (2))

Thus, ψ can be determined experimentally by measuring Λ', Λ''. From (5), it then follows that

$$M = \alpha l - \frac{1}{2} \ln |\varrho_0|. \tag{8}$$

where

$$M = -\frac{1}{2} \ln \cos \psi \quad \text{ist.} \tag{9}$$

If we now measure ψ for various analyzer lengths l (i.e., at constant frequency ν_0 for various k according to (2)), compute M from this, and enter it against l, we obtain a straight line. Its slope will then be the sought-for attenuation value α.

In determining ψ according to (7), it is more convenient not to measure waveguide wavelengths Λ' and Λ'' but rather the related frequencies ν' and ν'' or the free-space wavelengths λ', λ''. In the usual waveguide attenuations, the difference

$$\delta\nu = \nu'' - \nu' \qquad (10)$$

is small compared to ν_0. From (7) and the well known formula for the waveguide wavelengths

$$\Lambda = \frac{\lambda}{\sqrt{1-\left(\frac{\lambda}{\lambda_g}\right)^2}} \qquad (11)$$

the approximation

$$\psi = k\pi \cdot \frac{1}{1-\left(\frac{\nu_g}{\nu_0}\right)^2} \cdot \frac{\delta\nu}{\nu_0} \qquad (12)$$

is then derived. Here, λ_g and ν_g are the threshold wavelength or the cutoff frequency of the waveguide. From a higher approximation, we find a condition of validity for (12). It must be

$$\left|\frac{\delta\nu}{\nu_0}\right| \ll 4\left[\left(\frac{\nu_0}{\nu_g}\right)^2 - 1\right]. \qquad (13)$$

Further simplifications can be made for the borderline cases of a short and a long analyzer.

For a short analyzer, ψ is generall small. Development of (9) yields:

$$M = \left(\frac{\psi}{2}\right)^2 \qquad (14)$$

and, according to (6),

$$M = \left(\frac{X_Q}{Z_0}\right)^2. \qquad (15)$$

This relation may be used as long as

$$\left(\frac{\psi}{2}\right)^2 < \frac{3}{5} \qquad (16)$$

For a long analyzer, not only is $\delta\nu/\nu_0$ small, but this is the case also for the difference of neighboring resonance points:

$$\frac{\nu_0^{(k+n)} - \nu_0^{(k)}}{\nu_0^{(k)}} = \frac{\Delta_n \nu_0}{\nu_0} \qquad (17)$$

if $|n|$ is not too large.

It follows from (2) and (11) that

$$k = n \frac{\Lambda^{(k+n)}}{\Lambda^{(k)} - \Lambda^{(k+n)}} = n \cdot \frac{\nu_0}{\Delta_n \nu_0} \left[1 - \left(\frac{\nu_g}{\nu_0}\right)^2\right]. \qquad (18)$$

If this is introduced into (12), the result is

$$\psi = \pi n \frac{\delta\nu}{\Delta_n \nu_0}. \qquad (19)$$

A waveguide is long enough for this approximation if the same ψ is yielded from (19) for various n.

From (8), (9), and (19) we then obtain for the attenuation

$$\alpha = -\frac{1}{2l} \ln \frac{\cos\left(\pi n \frac{\delta\nu}{\Delta_n \nu_0}\right)}{|\varrho_0|} \qquad (20)$$

in Neper/m, if length l is measured in meters. In a long waveguide, the attenuation losses generally outweigh the losses of the shorting plunger. We can therefore set $|\rho_0| = 1$ without making any large errors and then obtain attenuation α directly from (20).

IV. Corrections

In the basic description of the measuring procedure, it was assumed that no losses occur in the coupling pin. In actuality this is not the case. Quantitative predictions concerning the magnitude of loss resistance R (see Fig. 2b) are obtained by measuring the amplitude transmission factor $|\tau|$ of the coupling pin while modulating its natural freequency ($X_Q = 0$). If R were equal to 0, the pin would have to block the waveguide entirely. Since losses do exist, the blocking effect is lessened. A simple computation yields, for $R/Z_0 \ll 1$,

$$|\tau| = 2 \cdot \frac{R}{Z_0}. \qquad (21)$$

Since the electrical field around the pin interacts with the wall of the waveguide, resistance R is also somewhat dependent on the waveguide attenuation. Values can be found in Fig. 6.

Resistance R is a function of the penetration depth of the pin. In order not to overcomplicate the following considerations, let us assume that R does not change with penetration depth. Taking this dependence into account would only result in an unnecessary refinement. A not very complex consideration -- which, however, will not be gone into here -- shows that circle K in Fig. 4 must be replaced by circle KR, as shown in the same figure. Further analysis -- for $R/Z_0 \ll 1$ - demonstrates that Eqs. (8) and (20) remain valid if $|\rho|_0$ is replaced by

$$|\varrho_0| \cdot \left(1 - 2\frac{R}{Z_0}\right) \qquad (22)$$

Accordingly, resistance R influences the measurement of α in a manner similar to the effect of the reflectivity coefficient of the shorting plunger.

A further idealized assumption was that the longitudinal resistances -iXL are negligibly small in the equivalent-circuit diagram of the coupling pin. These data are evaluated, in Fig. 7, confirming that $XL/Z_0 \ll 1$. If we now first assume

assume that these longitudinal resistances are independent of the penetration depth, then circle K must be replaced by a circle KL, which is turned clockwise against K about the angle

$$\varphi_L = 2 \cdot \frac{X_L}{Z_0} \qquad (23)$$

(Fig. 4). We shall neglect the derivation of (23). If the longitudinal resistances $-iXL$ actually were independent of the immersion depth, their effect would be compensated for in the measurement of $\delta\nu$. Equations (12) and (20) could remain unchanged. If, however, we do take into consideration the dependence on penetration depth, we find that factor $\delta\nu/\nu_0$ in Eq. (12) must be replaced by

$$\frac{\delta\nu}{\nu_0} + \left|\frac{\Delta X_L}{Z_0}\right| \cdot \frac{1 - \left(\frac{\nu_L}{\nu_0}\right)^2}{k\pi} \qquad (24)$$

and factor $\delta\nu/\Delta_n\nu$ in the argument of the cos-function of (20) by

$$\frac{\delta\nu}{\Delta_n\nu} + \frac{1}{\pi n} \cdot \left|\frac{\Delta X_L}{Z_0}\right|. \qquad (25)$$

where ΔXL indicates the difference of the longitudinal resistances for the two penetration depths which lead to the fitting. Since the penetration depths can be determined simultaneously with the measurement of the frequency differences, XL/Z_0 and $\Delta XL/Z_0$ can be read from Fig. 7, and with these values the corrections corresponding to (24) and (25) can be applied to (12) or (20).

In most cases, the corrections are so small -- with the design of the analyzer and pin suggested here -- that they can be neglected.

V. Experimental Results

Figure 8 shows the cross-section of two detachable brass analyzers with lines of intersection A - A and B - B. Their length is approximately 140 mm. The coupling pin is housed in a slotted sleeve. It was absolutely necessary to seal the small gaps between the sleeve and the pin with silver conductive lacquer so that the losses in the coupling pin would be sufficiently small and reproducible.

In the narrow gaps, the solvent of the conductive lacquer evaporates very slowly; the pin remains movable for several days. Thereafter, repainting is necessary.

Special emphasis was placed on ensuring that the pin moved at right angles to the longitudinal axis of the waveguide. Otherwise, length l of the resonator would not be equal between the two penetration depths which are required for fitting, and would cause very undesirable frequency distortions.

The distance between the coupling pin and shorting plunger is regulated to the desired resonator length l using a sliding gauge accurate to within 0.1 mm. The remaining air gaps are closed with conductive lacquer, as was mentioned earlier.

The two analyzers are equivalent. The disadvantage of section A - A, i.e., that the measuring accuracy is lessened to a greater extent by minor contamination of the sectional planes, is compensated for by the simpler insertion and closing of gaps of the shorting plunger and the simplification of the painting with conductive lacquer. Figure 9 presents typical measured values, corresponding to (8), that were obtained with these analyzers. The relative frequency differences $\delta\dot{\vartheta}/\nu_0$ fluctuate in magnitude between a few $1^0/00$ and several percent. The required measuring accuracy can just be obtained with good cavity ondometers (under certain conditions, after special calibration on a quartz standard).

Measurements were also taken on a third analyzer which consisted of a standard waveguide 1 m in length. From Fig. 9, we obtain

$$|\varrho_0|\left(1-2\frac{R}{Z_0}\right)=1-0{,}0028$$

(unnumbered eq.)

Thus $|\rho_0|(1-2R/Z_0$ =1 can justifiably be set equal to 1. The evaluation according to (22) with (20) can then be accomplished quickly. Admittedly, there are disadvantages in the greater use of material, problems in painting, and difficulty in cleaning.

Finally, Table 1 presents a few values for the attenuation measurements of an X-band waveguide painted with commercial silver conductive lacquer, for a frequency of about 10.5 GHz. For comparison, the attenuation measurement of the empty analyzer is given. The measuring accuracy should be approximately ±10%.

As was to be expected, (Morgan Ref.6), the attenuation measurement of the empty brass analyzer is somewhat larger compared to the idealized theoretical values (see, e.g., Meinke-Gundlach Ref. 3 p. 321) as a result of the roughness of the surface.

The thickness of the lacquer layers was so great --

as shown by control measurements -- that there was no noticeable effect of the metallic waveguide on the attenuation values of the conductive lacquers.

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FIGURES

1. Main measuring setup
2. Coupling pin and equivalent-circuit diagram (per Ref. 4)
3. Reflectivity coefficient of the analyzer
4. Matched circuits K, K_R, and K_L in the Smith diagram (transformed conductance diagram). The transformed conductances a are given in parentheses; the other numbers designate the coordinates in the cartesian x-y system.
5. Locus curve of a lossy shrt-circuited circuit as a function of frequency ν in the Smith diagram with matching circuit K. Cf. Fig. 4.
6. Losses of a silver pin (1.5 mm ϕ) in WR-90 waveguides with various attenuations as a function of resonance frequency or penetration depth.
7. Longitudinal resistances X_L (see Fig. 2) of a 1.5 mm ϕ pin in a WR-90 waveguide. The resonance points of the pin (X_0=0) are shown as dots. The curves were plotted using experimental data (from Refs. 4 and 5).
8. Cross-section of two detachable analyzers with intersection planes A-A and B-B.
9. Measuring points for evaluation according to Eq. 8). The measurements are for two coats of paint with Degussa 200, frequency 10.7 GHz.

Table 1. Attenuation measurements for an X-band waveguide with various conductive silver paintings.

Degussa conductive silver 200	0.51 dB/m
Degussa conductive silver 204	0.40 dB/m
Degussa conductive silver 245	0.68 dB/m
Degussa conductive silver 202 N	1.50 dB/m
Durrewachter Auromal 9	1.32 dB/m
Achesen DAG 1415	1.43 dB/m
Brass	0.29 dB/m