AN ALTERNATIVE BROADBAND METHOD FOR AUTOMATIC MEASUREMENT OF THE COMPLEX PERMEABILITY AND PERMITTIVITY OF MATERIALS AT MICROWAVE FREQUENCIES

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ABSTRACT

An alternative broadband method for the simultaneous measurement of the complex permeability and permittivity of lossy microwave solid materials or liquids by automatic network analyzer technique is reported. Both theoretical and practical aspects will be presented in details. Calibration parts, samples with sample holders correlated to measured data will be demonstrated.

INTRODUCTION

Application of materials at microwave frequencies often requires the exact knowledge of material parameters such as permeability and permittivity. Sometimes these parameters can fairly differ from those characterizing the material at lower frequencies. In particular this is the case with microwave absorbing materials. Both parameters are considered to be complex quantities:

$$\varepsilon_r = \varepsilon' - j\,\varepsilon''$$

$$\mu_r = \mu' - j\,\mu''$$

Generally both ε' and μ' can be different from unit and both ε'' and μ'' can be different from zero. Therefore two independent complex quantities are to be measured simultaneously in order to be able to calculate these two complex material parameters.
The achievable frequency range of the measurement setup is one of the most important characteristics of the method, so there are waveguide, coaxial and free-space versions of the same measurement basis (1). The method described here is suitable for broadband measurement of materials which have both dielectric and magnetic characteristics with a relatively high loss $\tan\delta$ (>0.1). For low loss $\tan\delta$ materials (<0.01), the basic measurement principle also gives valid results for the dielectric or magnetic constants (ε', μ') measurement, but the measurement uncertainty of loss factor (ε'' , μ'') is high.

In this open forum paper both theoretical aspects (see Appendix) and the results of practical experiments will be presented. Using the opportunity to display hardware, also sample holders, calibration parts and measured samples will be demonstrated.

BASIC METHOD OF THE MEASUREMENT

Most commonly a reflection (S_{11}) and a transmission (S_{21}) parameter is measured for wide-band, easy-to-perform, accurate characterization of the material (2). The advantage of the computer controlled automatic vector network analyzer technique appeared in the last decade gives the possibility to perform the basic measurements and computations for hundreds of step-by-step points of frequencies in 'almost real-time'.

An alternative broadband method can be adapted by measuring two reflection coefficients for two different thicknesses of the same material ($S_{11}^{(d)}$ and $S_{11}^{(2d)}$). The basic theory is briefly described in the Appendix. It is shown that the most useful cases are when the thicknesses d, 2d or d, 3d or 2d, 4d are used, where d is the smallest available thickness of the material to be measured. It is worth noting that applying four different sample thicknesses d, 2d, 3d and 4d of the same material, the number of independently evaluated ε's and μ's are three, and therefore an appropriate data-processing method can give the possibility to increase the measurement accuracy.

The measurement setup shown in Fig. 1. consists of a vector-network analyzer and the sample holder, which is either a waveguide or a coaxial extension of the analyzer port. The sample holder is short-circuited at the end. The main purpose to apply this extension line is on one hand to separate the sample from the reference plane of the equipment, in order to protect the port of the network analyzer. On the other hand a twist can be given to it, if necessary, to take the sample holder into an upright position using a waveguide knee-joint or a coaxial extension cable. In this way solid materials and even liquids can be measured which is the ultimate advantage of this measurement method.

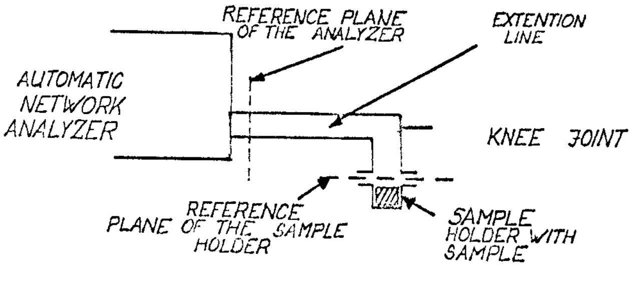

Fig. 1.
The measurement setup

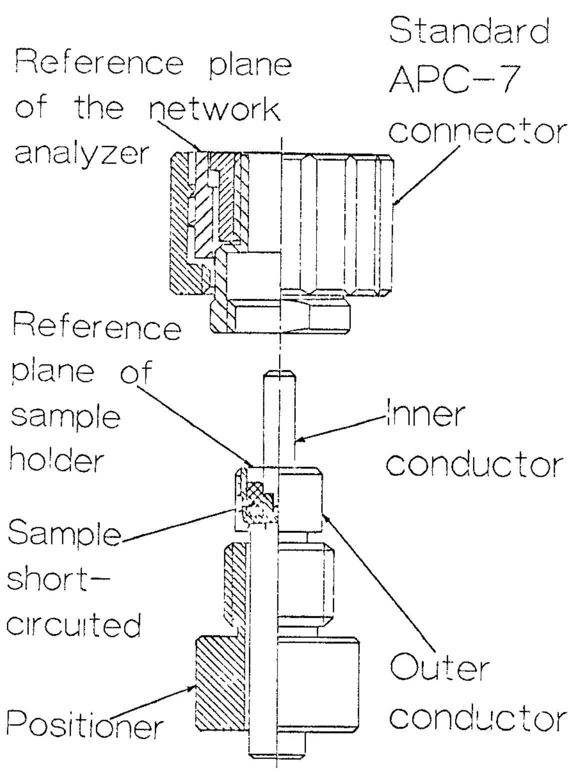

Fig. 2.
The scheme of the test fixture

TEST FIXTURES

To avoid the generation of leaky waves caused by spurious modes in the sample itself, and so to achieve the widest available measurement bandwidth, a coaxial rather than waveguide sample holder are to be used. In our measurement setup the protecting extension line has a standard connector (e.g. APC-7) at the reference plane of the equipment and a normal coaxial flange at the actual reference plane.

A very accurate calibration should be verified at the actual reference plane on condition that the previous enhanced system calibration was correct. This is very important because the complex functions of ε_r and μ_r are rather complicated and the cumulative error could cause a significant degradation of the measurement accuracy (see Appendix). As a result, a very simple fabrication method can meet this requirement, which is a further advantage of the method. Calibration hardware and measured data of the correlated calibration will be demonstrated.

A very simple sample holder is shown in Fig. 2. as an example. Both the length of the holder and the thickness of the sample itself can be changed flexibly. An optimum thickness of the material do exist because of the $(2n+1) \cdot \lambda_g/4$ transformer effect. This means that maximum and minimum S_{11} occur when the thickness is $(2n-1) \cdot \lambda_g/4$ and $n \cdot \lambda_g/2$, respectively. If the sample length is selected to be $(2n-1) \cdot \lambda_g/4$ the uncertainties for ε_r and μ_r will be minimized.

MEASUREMENT RESULTS

Typical calculated ε_r and μ_r results of a measured ECCOSORB absorbing material in the frequency range of 2 to 12 GHz are shown in Fig. 3.

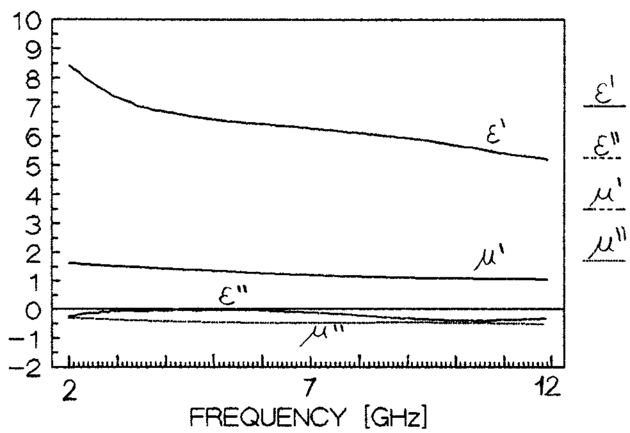

Fig. 3.
Measured data of ECCOSORB absorbing material

The quarterwave-type absorbing sheet had a thickness of d=2.03 mm. Several samples

cut from the same sheet was tested as paired measurements for thicknesses d, 2d and also for 2d, 4d as a simple check of the method. Using the same ANA calibration, the difference of the results obtained by repeated measuring routines of the same samples is smaller than 1 percentage on condition that the samples were fitted properly. Different samples prepared from the same sheet resulted slightly different curves, but any of the four calculated parameters was within 5 percentage in the whole frequency band.
As an other example, a low-loss TEFLON-style material was tested (see Fig. 4.), which has ε' =2.03 and $\tan\delta<10^{-3}$ measured at frequency f=10MHz. In this case the results are acceptable for the dielectric and magnetic constant, but the uncertainty of the loss factors are high, according to the theoretical consideration of the measurement accuracy.

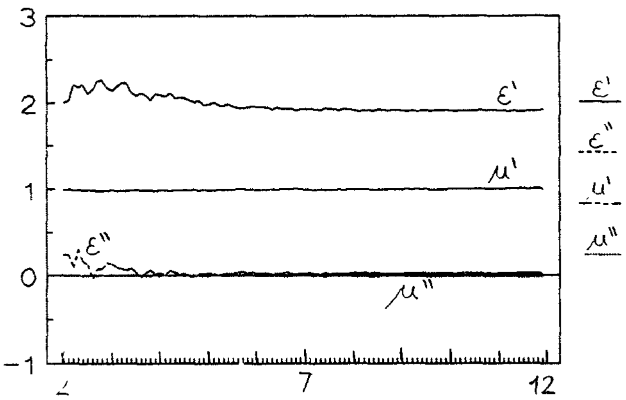

Fig. 4.
Measured data of TEFLON-style dielectric material

MEASUREMENT ACCURACY

Several sources of error must be considered in this measurement. Some of them are considered to be reproducible errors, such as one part of the instrumentation errors, higher order mode excitation, uncertainty of the sample form and sizes, as well as the surface roughness of the material. Others are considered to be non-reproducible errors such as the rest part of instrumentation, errors caused by the accidental air gap between material and conductors due to nonaccurate position of fitted sample and the unintentional material inhomogeneity.

Instrumentation errors
Concerning of the instrumentation errors refer to the ANA's technical manual.

Higher order mode excitation
The first higher order mode appears in APC-7 connectors at frequency about 20.5 GHz. It should be divided by $|\sqrt{\varepsilon_r \mu_r}|$ for coaxial lines filled with materials. If the sample was not fitted into the sample holder properly, the first higher mode could appear. A typical example is shown in Fig. 5., where $|\sqrt{\varepsilon_r \mu_r}|$=4.3 and f=4.7 GHz, their product really corresponds to the 20.5 GHz.

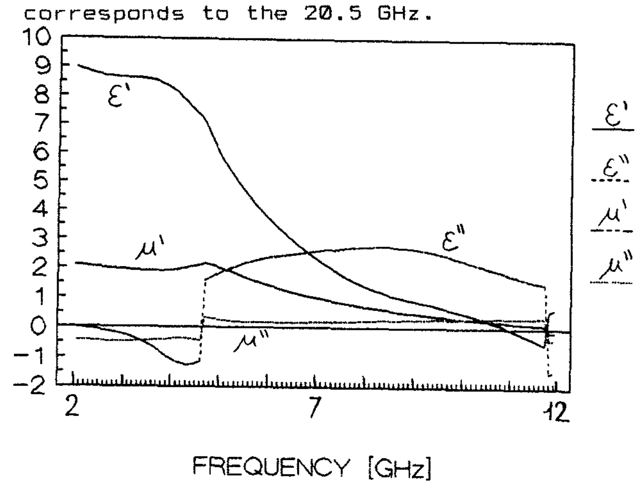

Fig. 5.
Example of appearing of higher order mode

Uncertainty of the form and sizes
The uncertainty of the form and sizes of the sample degrade the accuracy, as the calculation is only valid for the geometrically ideal samples. This error can be avoided applying a very strict sample preparation process. Since the method presented here was designed for a rapid qualification of materials the expenses of the strict sample preparation processes are unacceptable demands.
The surface roughness is the special case of the size uncertainty. Practically it should be kept below $\lambda_g/20$.

Non-reproducible errors
Their influence could be decreased by the measurement of a large set of samples.

Time-domain
Gating is a useful tool in enhanced measurements, which increases the measurement accuracy. The effect of re-reflections appears as noise in the time-domain response. Sample holder testing also required time-domain analysis.

SOFTWARE CONSIDERATIONS

The advanced software for an IBM-AT compatible computer can not only do the computations within one minute, but is also capable to provide extra user-defined services, such as:

- to calculate flexibly ε_r and μ_r from all possible pair combinations of measured data at different thicknesses,
- to perform comparison between permeability or permittivity data calculated from differently paired measurements,
- and to perform their smoothing or averaging,
- to cancel questionable data,
- to simulate the overall accuracy.

CONCLUSION

An alternative, easy-to-perform, wide-band method for the simultaneous measurement of the complex permeability and permittivity of lossy microwave materials or liquids by automatic network analyzer technique have been reported. The test fixture which meets the requirements of this method is very simple. The results obtained on both an ECCOSORB absorbing material and TEFLON-style dielectric material are also presented.

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APPENDIX

As an example calculation method for two samples of a material with two different thicknesses d and 2d is shown here. It can be written for the measured $S_{11}^{(d)}$ and $S_{11}^{(2d)}$ from flowing-chart:

$$S_{11}^{(d)} = \frac{\Gamma - T^2}{1-\Gamma\cdot T^2}$$

for length d.

$$S_{11}^{(2d)} = \frac{\Gamma - T^4}{1-\Gamma\cdot T^4}$$

for length 2d.

Solving the equations ε_r and μ_r can be calculated as follows:

$$\Gamma = K\pm\sqrt{(K^2-1)}$$

where:

$$K = \frac{\{(S_{11}^{(d)})^2+2\cdot S_{11}^{(d)}-1\}\cdot S_{11}^{(2d)}-(S_{11}^{(d)})^2+2\cdot S_{11}^{(d)}+1}{2\cdot\{(S_{11}^{(d)})^2+S_{11}^{(2d)}\}}$$

$$T = \sqrt{\{L\pm\sqrt{(L^2-1)}\}}$$

where:

$$L = \frac{(S_{11}^{(d)}+1)\cdot(S_{11}^{(2d)}-1)}{2\cdot\{S_{11}^{(d)}-S_{11}^{(2d)}\}}$$

$$\frac{1}{\Lambda^2} = -\{\frac{1}{2\cdot\pi\cdot d}\cdot\ln(1/T)\}^2$$

hence:

$$\mu_r = (1+\Gamma)/[\Lambda\cdot(1-\Gamma)\cdot\sqrt{(\lambda_o^{-2} - \lambda_c^{-2})}]$$

$$\varepsilon_r = (\Lambda^{-2} - \lambda_c^{-2})\cdot\lambda_o^2/\mu_r$$

Similar procedure may be applied for measurements with samples' thicknesses d and 3d, or 2d and 4d, too.

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(2) Hewlett Packard product note No. 8510-3, 'The Measurement of Both Permittivity and Permeability of Solid Materials', (5954-1535) August, 1985.