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Obstacle-based self-calibration techniques for the determination of the permittivity of liquids

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Abstract. In this contribution, different obstacle-based self-calibration techniques for the measurement of the dielectric properties of liquids are investigated at microwave frequencies. The liquid under test is contained inside a waveguide, which is connected to the ports of a vector network analyzer. The permittivity of the liquid is characterized on the basis of the measured scattering parameters.

In order to extract the material parameters precisely and to eliminate systematic errors of the setup, calibration measurements have to be performed. For this purpose, different self-calibration methods based on the displacement of an obstacle are considered. The presented methods differ in that way, that either transmission and reflection measurements or purely reflection measurements are performed. All these methods have in common that the material parameters are already calculable within a so-called self-calibration procedure. Thus, a full two-port calibration of the whole setup is not necessary. Furthermore, the methods can be realized effectively in a practical setup having the advantage that a rearrangement of the setup is not needed for the material parameter measurements and that the liquid under investigation can pass continuously through the measurement cell. This might be of interest for the application in an industrial process, enabling the continuous flow of the material while the parameter characterization can take place at the same time.

1 Introduction

At microwave frequencies, the dielectric properties of liquids can be measured by means of guided-wave travelling-wave methods Clarke et al. (2003). The material parameters are determined on the basis of the measured complex scattering parameters using a vector network analyzer (VNA). For this purpose, the dielectric sample is filled into a measurement cell, which can be a coaxial line or a rectangular or circular waveguide.

The measurements with the VNA are influenced by systematic errors due to transmission losses, reflections at the measurement ports and other non-idealities of the setup. These systematic errors can be represented by transmission matrices describing the error two-ports $\mathbf{G}^{-1}$ and $\mathbf{H}$, as known from the error description of two-port vector network analyzers according to the 7-term-model and as shown in Fig. 1. In order to eliminate these systematic errors and to obtain the error-corrected material parameters of the specimen, multiple calibration measurements have to be performed.

A well-known method for the material characterization is the TL-method (through, line) (Engen and Hoer, 1979; Eul and Schiek, 1991), which is based on the measurement of the scattering parameters of two lines with a difference Δl in length as shown in Fig. 2.

With the measured wave parameters m_1 to m_4 from Fig. 1 two measurement transmission matrices $\mathbf{M_T}$ and $\mathbf{M_L}$ can be constructed. The transmission matrix $\mathbf{M}$ can be written in its general form as:

$$\mathbf{M} = \begin{bmatrix} m_1' & m_1'' \\ m_2' & m_2'' \end{bmatrix} \begin{bmatrix} m_3' & m_3'' \\ m_4' & m_4'' \end{bmatrix}^{-1} = \mathbf{G}^{-1}\mathbf{T_D}\mathbf{H} \tag{1}$$

where the one-dashed and two-dashed terms represent the measured wave parameters in dependance of the feeding direction of the generator signal, either from port 1 or port 2. $\mathbf{T_D}$ is the transmission matrix of the device connected to the ports of the analyzer. Thus, the propagation constant γ of the line standard can be calculated by:

$$\begin{aligned} trace\{\mathbf{M_T}\mathbf{M_L}^{-1}\} &= trace\{(\mathbf{G}^{-1}\mathbf{T_T}\mathbf{H})(\mathbf{G}^{-1}\mathbf{T_L}\mathbf{H})^{-1}\} \\ &= trace\{\mathbf{T_T}\mathbf{T_L}^{-1}\} \\ &= trace\left\{\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} e^{-\gamma\Delta l} & 0 \\ 0 & e^{\gamma\Delta l} \end{bmatrix}^{-1}\right\} \\ &= e^{\gamma\Delta l} + e^{-\gamma\Delta l} \ , \end{aligned} \tag{2}$$

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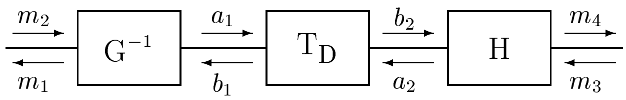

Fig. 1. Error model of the measurement system.

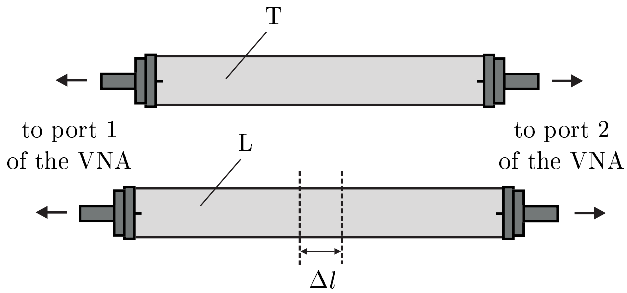

Fig. 2. Setup of the TL-method, based on two lines of different lengths.

where the operator *trace* stands for the calculation of the trace of a matrix. The complex permittivity $\epsilon_r = \epsilon_r' - j\epsilon_r''$ can thus be calculated for a TEM waveguide on the basis of the propagation constant γ:

$$\epsilon_r = \left(\frac{\gamma \cdot c}{2\pi f}\right)^2 , \tag{3}$$

where f is the frequency and c the speed of light in vacuum. One disadvantage of this method is that two lines of different lengths are needed which have to be connected to the ports of the analyzer. Thus, a rearrangement of the measurement setup becomes necessary, enlarging the effort of the measurements.

2 Obstacle-based methods

Based on the displacement of an obstacle within a waveguide being filled with the liquid under investigation and on the measurement of the scattering parameters for different positions of the obstacle, the permittivity of the liquid under test can be determined. In the following different variants of such obstacle-based methods will be presented.

2.1 LNN-method

In Fig. 3 a measurement setup for the line-network-method (LNN) (Heuermann and Schiek, 1997; Rolfes and Schiek, 2006) is shown, which enables a material characterization within the same setup without the need for a rearrangement. Instead of the two lines as necessary for the thru-line method, a so-called obstacle is used, which can be realized as a dielectric plate with unknown parameters. For the measurements,

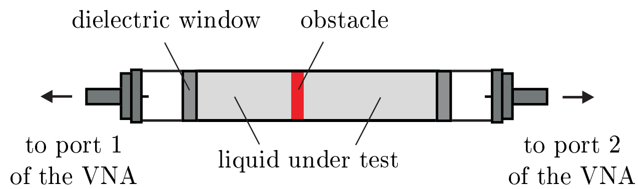

Fig. 3. Measurement system for the material characterization based on the line-network-method.

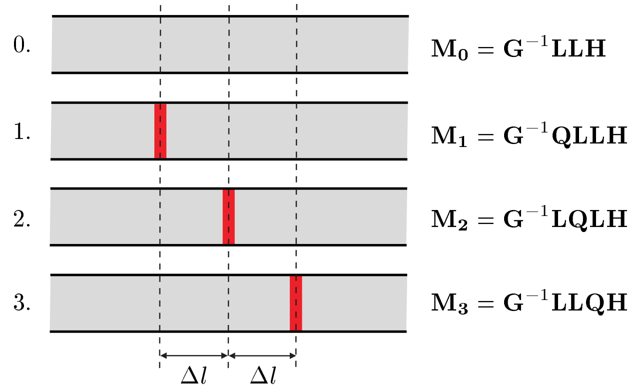

Fig. 4. Structures for a full two-port calibration according to the line-network-method.

the waveguide is filled with the specimen. The liquid under test can either be kept in a static position without any movement or in a dynamic state, passing through the waveguide. The latter variant is of interest for the application in an industrial process, enabling the continuous flow of the material, while the parameter characterization can take place at the same time. In order to keep the specimen in a defined position two dielectric windows can be used as shown in Fig. 3.

For a full two-port calibration of the whole system, the scattering parameters of the setup have to be measured for four different positions of the obstacle. First, the measurement of the waveguide without obstacle has to be performed (pos. 0 in Fig. 4). Next, the obstacle is placed at three consecutive, equidistant positions (1, 2, 3) within the waveguide, as shown in Fig. 4. The displacement of the obstacle can be accomplished with the help of a step motor. For the material characterization it is already sufficient to perform the network analyzer measurements with the three latter obstacle positions (1, 2, 3). This has the advantage, that the obstacle can be left completely within the waveguide, reducing the complexity of the measurement setup. Thus the test cell as shown in Fig. 3 can be used for the permittivity measurements, with the obstacle being left in the setup. For the determination of the material parameters, the measured values for the three different positions are arranged in measurement transmission matrices $\mathbf{M_1}$, $\mathbf{M_2}$ and $\mathbf{M_3}$, according to Eq. (1).

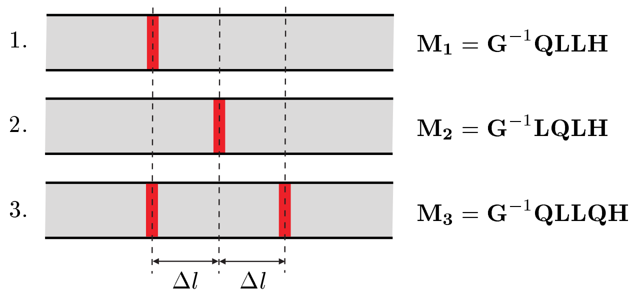

Fig. 5. Measurement structures of the multiple-N-method.

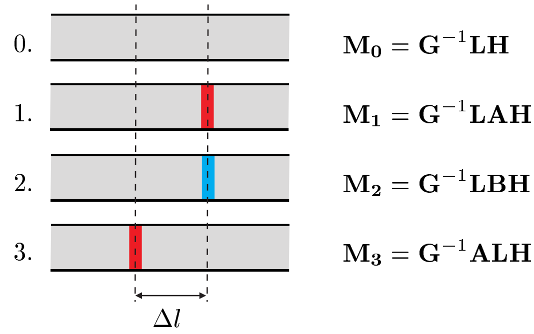

Fig. 6. Measurement structures of the 2-state-multiple-N-method.

As already described in Fig. 4, these measurement matrices are equal to the product of the transmission matrices $\mathbf{G}^{-1}$ and $\mathbf{H}$, representing the systematic errors of the setup including the VNA, and matrices $\mathbf{L}$ and $\mathbf{Q}$, representing the line elements between the obstacle positions and the obstacle, respectively. The obstacle needs not to be symmetrical. Furthermore, the obstacle parameters as well as the line propagation terms can be unknown. Calculating the traces of the following matrix combinations

$$\delta_1 = trace\{\mathbf{M_1}\mathbf{M_2}^{-1}\} \tag{4}$$

$$\delta_2 = trace\{\mathbf{M_1}\mathbf{M_3}^{-1}\} \tag{5}$$

and with

$$\delta = \frac{\delta_2 - 2}{\delta_1 - 2} \tag{6}$$

the propagation constant of the material within the waveguide can be calculated,

$$e^{-\gamma \cdot \Delta l} = \pm \frac{\sqrt{\delta}}{2} \pm \sqrt{\frac{\delta}{4} - 1} \ , \tag{7}$$

where Δl is the distance between two obstacle positions. As can be seen, Eq. 7 has four possible solutions. In order to choose the appropriate solution an a priori knowledge of the approximate value of $\gamma \cdot \Delta l$ is necessary. Thus, the permittivity can be determined, if the relationship between the propagation constant and the waveguide dimensions are known, also for a non-TEM waveguide.

2.2 Multiple-N method and 2-state-Multiple-N-method

Further obstacle-based methods with transmissive obstacles can be applied for the calibrated and error-corrected determination of the material parameters of a specimen within a waveguide. Possible measurement structures for the multiple-N and the 2-state-multiple-N-method (Rolfes and Schiek, 2002b) are depicted in Figs. 5 and 6. As well as for the line-network-method, obstacle networks have to be placed at different positions within the waveguide. For the multiple-N-method a second obstacle of the same type is needed whereas for the 2-state-multiple-N-method a second obstacle with different characteristics is needed. This can be realized by choosing obstacle materials with different permittivities. However, for these two methods it is necessary to perform measurements with all structures as shown in Figs. 5 and 6, having the drawback for the multiple-N-method that a further obstacle has to be inserted into the setup, and for the 2-state-multiple-N-method that two different obstacles characterized by matrices $\mathbf{A}$ and $\mathbf{B}$ have to be inserted into the waveguide. This makes the realization and the measurements more complex. Based on the determination of the propagation constant, the permittivity can be calculated, similar to the previously described line-network-method. For the realization of the test cell it is mandatory that higher order modes are neither able to propagate nor to be excited. This can be achieved by realizing obstacles which are completely filling the waveguide and have plane surfaces perpendicular to the guide. Furthermore, these obstacles have to be homogenous and their permittivity has to be chosen suitably, i.e. it does not have to be too high.

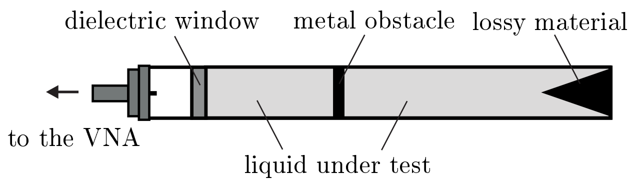

Fig. 7. One-port test cell for the reflective method.

2.3 Reflective method

For the reflective method, a one-port setup as shown in Fig. 7 is already sufficient. The setup consists of a waveguide, e.g. a rectangular waveguide, which is connected to one port of the VNA. A reflective obstacle, which can be realized as a metal plate, has to be placed at four consecutive positions within the waveguide, being filled with the specimen, as can

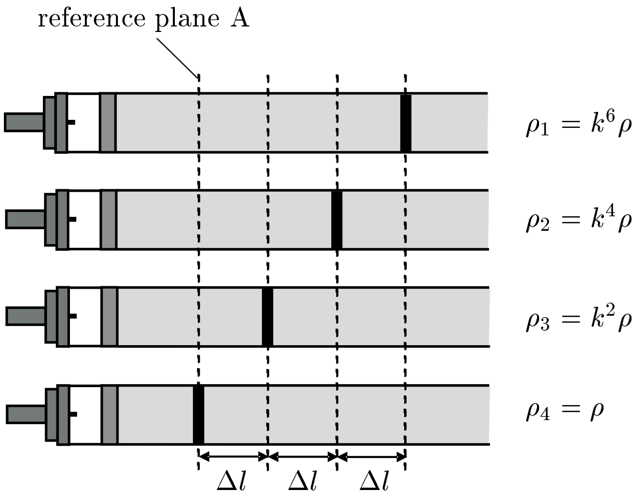

Fig. 8. Obstacle positions for the reflective methods.

be seen in Fig. 8. The waveguide is terminated on the other side by a lossy material, in order to inhibit resonances.

For the reflective method the calibration configurations are described with the help of the reflection coefficient ρ and the line parameter k, which can be unknown. Based on the setup in Figs. 7 and 8, the reflection coefficients ρ_i at the reference plane A are defined as follows:

$$\rho_1 = k^6\rho, \tag{8}$$

$$\rho_2 = k^4\rho, \tag{9}$$

$$\rho_3 = k^2\rho, \tag{10}$$

$$\rho_4 = \rho \tag{11}$$

With respect to the systematic errors according to the error model in Fig. 1 and with $\tilde{\mathbf{G}}=\mathbf{G}^{-1}$ the following equation results for the measurement of the i-th reflection coefficient ρ_i, i=1, ..., 4:

$$\begin{bmatrix} m_{1,i} \\ m_{2,i} \end{bmatrix} = \tilde{\mathbf{G}} \begin{bmatrix} b_{1,i} \\ a_{1,i} \end{bmatrix} = \tilde{\mathbf{G}} \begin{bmatrix} \rho_i a_{1,i} \\ a_{1,i} \end{bmatrix} \tag{12}$$

In dependance of the measured reflection coefficients ν_i the following bilinear transformation follows:

$$\nu_i = \frac{m_{1,i}}{m_{2,i}} = \frac{\tilde{G}_{11}\rho_i a_{1,i} + \tilde{G}_{12}a_{1,i}}{\tilde{G}_{21}\rho_i a_{1,i} + \tilde{G}_{22}a_{1,i}} = \frac{\tilde{G}_{11}\rho_i + \tilde{G}_{12}}{\tilde{G}_{21}\rho_i + \tilde{G}_{22}} \tag{13}$$

also known as Möbius-transformation, being generally defined as,

$$x_j = \frac{C_1 y_j + C_2}{C_3 y_j + C_4} \tag{14}$$

where the two variables x_j and y_j correspond to the measurement value ν_i and the unknown calibration standard parameter ρ_i and the constants $C_1, \ldots, C_4$ represent the error two-port parameters of Eq. (13). On the basis of the measurement of four reflection coefficients, four equations of the type of Eq. (13) result, so that the unknown error parameter $\tilde{G}_{ik}$ can be eliminated. This can be performed with the help of the cross ratio

$$\frac{(y_1 - y_2)(y_3 - y_4)}{(y_1 - y_4)(y_3 - y_2)} = \frac{(x_1 - x_2)(x_3 - x_4)}{(x_1 - x_4)(x_3 - x_2)} \tag{15}$$

which generally holds for a bilinear transformation as given in Eq. (14). An equation can thus be constructed, which only depends on the unknown line parameter $k=e^{-\gamma\Delta l}$.

$$\begin{aligned} \nu &= \frac{(\nu_1 - \nu_2)(\nu_4 - \nu_3)}{(\nu_1 - \nu_3)(\nu_4 - \nu_2)} \\ &= \frac{(\rho_1 - \rho_2)(\rho_4 - \rho_3)}{(\rho_1 - \rho_3)(\rho_4 - \rho_2)} \\ &= \frac{(k^6\rho - k^4\rho)(\rho - k^2\rho)}{(k^6\rho - k^2\rho)(\rho - k^4\rho)} \\ &= \frac{k^2}{(1+k^2)^2} \end{aligned} \tag{16}$$

The unknown reflection coefficient ρ as well as the error two-port parameters are both eliminated and the following equation results for the determination of the propagation constant and thus the permittivity.

$$k = \pm\frac{1}{2\sqrt{\nu}} \pm \sqrt{\frac{1}{4\nu} - 1} \tag{17}$$

Like the line-network-method this method has a very compact solution and is easy to realize in a practical setup.

3 Simulation results

For the verification of the different obstacle based methods and for the determination of the material parameters of dielectric specimens, various simulations were performed. By means of an electromagnetic field simulator, CST Microwave Studio, the electromagnetic properties of the measurement setup, based on a realization in a rectangular waveguide, were investigated. An obstacle network filling completely the waveguide as well as a dielectric obstacle with holes, enabling the continuous flow of a probe liquid within the test fixture were considered. Based on the simulated scattering parameters describing the propagation in the measurement cell, the further evaluation of the material parameters was investigated. Some results for the determination of the permittivity of a specimen within a frequency range of 8.2 GHz to 12.5 GHz are shown exemplarily in Fig. 9. A rectangular X-band waveguide 200mm in length, a dielectric obstacle with ϵ_r=3.2 and 5 mm in length and liquids with different permittivities were considered. The permittivity of the obstacle must differ from the permittivity of the sample material. The application of the multiple-N- and the 2-state-multiple-N-method as well as the reflective method, led to similar results. Within the simulations, no errors occur.

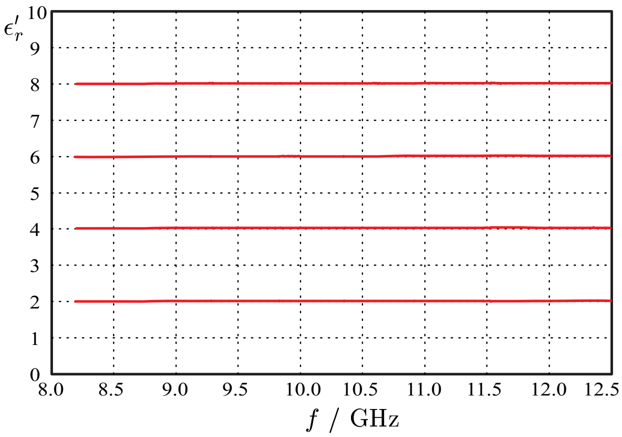

Fig. 9. Simulation results for the determination of the permittivity according to the line-network-method.

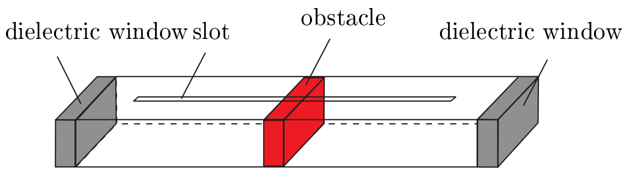

Fig. 10. Schematic setup of the measurement test cell for the line-network-method.

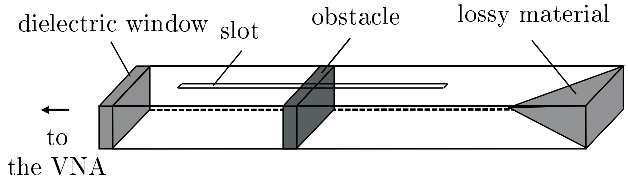

Fig. 11. Schematic setup of the measurement test cell for the reflective measurements.

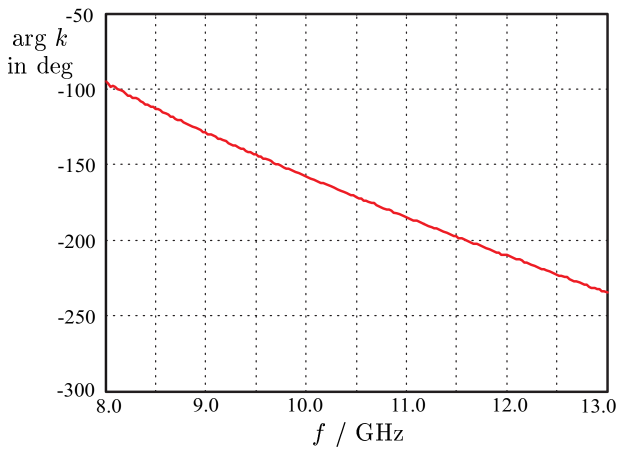

Fig. 12. Measured phase of air as a DUT based on the line-network-method.

4 Measurement results

Measurements were performed on the basis of a vector network analyzer and a rectangular waveguide measurement cell in X-band, as shown schematically in Fig. 10 for the line-network-method and in Fig. 11 for the reflective method.

The obstacle network is inserted into the waveguide. By a slot on top of the waveguide the obstacle can be displaced and oriented precisely. Furthermore, the slot can be used for the filling of the test cell with the specimen. On both ends of the measurement cell for the transmission measurements and on one end for the reflective measurements, respectively, a waveguide filled with a dielectric plate serves as a dielectric window. This allows to keep the liquid under test in a defined position within the test cell, filling it completely. This makes the measurements robust against level changes of the liquid as for example due to the displacement of the obstacle. In order to verify the functionality of the measurement system, measurements with air as a DUT, i.e. without any filling of the waveguide test cell, were performed first. For the line-network-method, an obstacle made from the commercial dielectric material PEI was used with a thickness of 4 mm, filling the waveguide nearly completely. Three separate measurement positions were considered, with the obstacle being displaced consecutively by a distance of 5 mm. In Fig. 12 the angle of the calculated propagation constant is shown. Based on Eq. (7) and an approximate knowledge of the term $\gamma \cdot \Delta l$, the appropriate solution was chosen. With the PEI obstacle it turned out that one solution was valid for the whole frequency range from 8 to 13 GHz. In Fig. 13 the determined permittivity is depicted. Differing from the TEM propagation in Eq. 3, a correction term $\epsilon_{r,corr}$ has to be added in order to account for the propagation in the rectangular waveguide

$$\epsilon_r' = \left(\frac{\gamma \cdot c}{2\pi f}\right)^2 + \left(\frac{c}{2a \cdot f}\right)^2 \tag{18}$$

where a=22.86 mm is the broadside width of the used rectangular X-band waveguide. The measurements show very good results, the measured dielectric constant of air is very close to 1, as can be observed in Fig. 13.

Similar measurements were performed on the basis of the reflective methods, leading to similar results.

Furthermore, measurements for the determination of the dielectric constant of different DUTs were performed also with varying obstacle position distances and also varying dielectric parameters for the obstacle. By Rolfes and Schiek (2006), measurement results for the determination of the permittivity of rape oil based on the line-network-method have already been presented Fig. 14. Here, better measurement

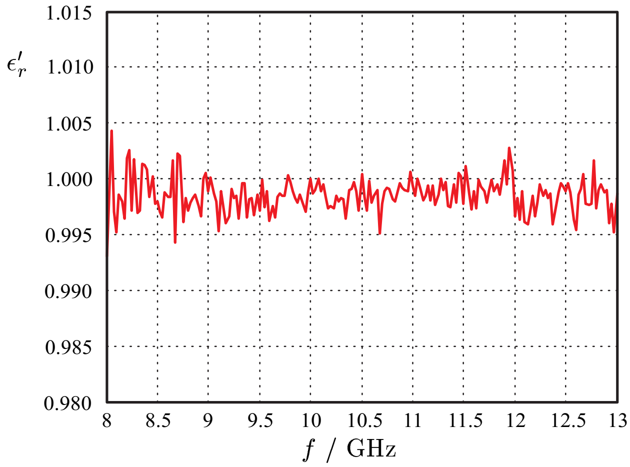

Fig. 13. Measured permittivity of air based on the line-network-method.

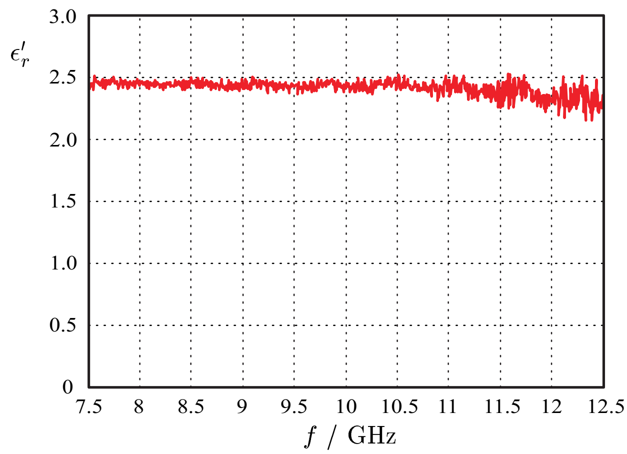

Fig. 14. Measured permittivity of rape oil as a DUT based on the LNN-method.

results for the reflective method with rape oil as a DUT are shown in Fig. 15. The obstacle was placed at four consecutive positions in a distance of 4 mm. In the frequency range of 8 GHz up to 13.5 GHz, the measured values are close to 2.4 and show a nearly constant characteristic over frequency. One of the main advantages of both line-network- and reflective methods is that a measurement of the test cell without obstacle is not needed. This helps to reduce the effort of the measurements. The DUT can be left within the test cell as well as the obstacle network for all measurements.

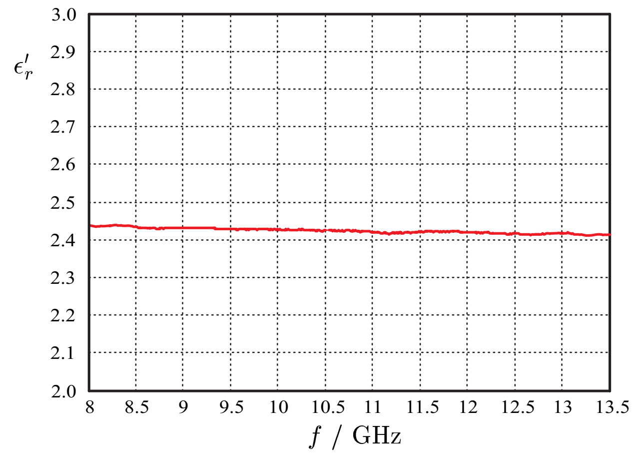

Fig. 15. Measured permittivity of rape oil as a DUT based on the reflective method.

5 Conclusions

For the determination of the permittivity of liquids based on the measurement of the scattering parameters using a vector network analyzer, different methods like the line-network-method and the reflective method are presented. Both methods are based on the displacement of an obstacle network within a measurement cell filled with the dielectric specimen. Both methods have in common that the measurements can be realized by means of a compact measurement setup. An extensive rearrangement of waveguide components is not necessary. The liquid under investigation can pass continuously through the measurement cell. This might be of interest for the application in an industrial process, enabling the continuous flow of the material while the parameter characterization can take place at the same time. Measurement results verify the robust functionality of the methods.

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