Calibration of a Lens-Focussed Reflectometer by Means of a Mixed Time/Frequency Domain Method

Gerhard L. Friedsam and Erwin M. Biebl

Lehrstuhl für Hochfrequenztechnik, Technische Universität München, Arcisstraße 21, 80333 München, Germany

ABSTRACT

A lens-focussed reflectometer operating in the 75-95 GHz frequency range for measuring the square of the complex transmission coefficient of planar samples for different angles of incidence and polarization states is presented. The systematic errors of the set-up are reduced by employing a new advanced time/frequency domain calibration method. Experimental results obtained with the lens-focussed reflectometer and with a free-space transmission measurement system are in good agreement. The deviation in the magnitude and in the phase of the measured curves are less than 1.0% and 1.0°, respectively.

INTRODUCTION

The traditional calibration method for linear error correction of waveguide or coaxial reflection measurements uses a load, a short circuit, and a open circuit or a offset short with known phase shift [1]. The imperfect reflectometer is modeled as an ideal reflectometer, which consists of a normalized voltage source, and an error network, which groups the linear systematic errors of the real measurement set-up. The error model has three relevant factors, namely the directivity, the source impedance match, and the reflection response. The three error factors are determined by measuring the system response using three independent standards with known frequency responses.

The traditional calibration procedure can be implemented in free-space by establishing calibration standards in the free-space medium. The load standard is obtained by inserting absorbing material into the free-space measurement path. The short standard and the offset short standard with known phase shift is realized by a metal plate. The traditional calibration method has been successfully applied for free-space reflectometers at submillimeter wavelengths [3] and for reflectometers, where the influence of secondary reflections are negligible [2]. In the millimeter wave range the error model for the lens-focussed reflectometer normally differs from traditional error models for closed measurement systems, because the primary reflection and the parasitic reflections in free space have different beam profiles. Due to nonlinear effects caused by the variation of the beam profile for each parasitic reflection a separate error factor has to be considered. By applying a time domain gating technique the higher order parasitic reflections in the free space can be suppressed. The number of the necessary error factors can be limited.

In this paper we present a novel mixed time/frequency calibration procedure for a lens-focussed reflectometer. The calibration method covers both the errors due to multiple reflections within the reflectometer and due to the non-ideal directivity of the set-up. The lens-focussed reflectometer has been designed to determine the square of the complex transmission coefficient of planar samples for different angles of incidence and both polarization states in the W-band from 75 GHz to 95 GHz. The measured data can be used to calculate the complex permittivity of the sample.

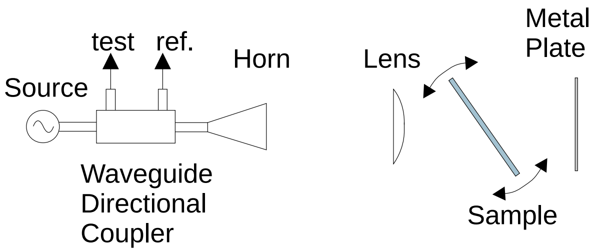

Figure 1: Block diagramm of the measurement set-up.

MEASUREMENT SET-UP

In Fig. 1 the measurement set-up is depicted. The key components of the measurement set-up are a millimeter wave source, a waveguide directional coupler, a profiled corrugated horn, a dielectric lens, and a reflector. The Gaussian beam excited by the profiled corrugated horn antenna is collimated by means of a dielectric lens. In order to ensure that the location of the output beam waist is independent of frequency, the distance between the input waist and the lens is equal to the focal length of the lens [4]. The reflector is located at the position of the output waist. It is realized by a plane metal plate. The distance between the lens and the reflector can be varied by means of a precision motor driven translator. In order to minimize diffraction effects the diameter of the invested samples is larger than eight times the radius of the Gaussian beam at sample position. The sample holder is mounted on a precision motor driven rotary stage. The reference signal and the test signal are measured with a waveguide directional coupler. An automatic network analyzer HP8510 is used to analyze the received signals. Employing this set-up we measure the square of the complex transmission coefficient of planar samples for different angles of incidence and for both perpendicular and parallel polarisation in the 75 GHz to 95 GHz range.

CALIBRATION PROCEDURE

Fig. 2 gives a simplified signal flow graph representation of the lens-focussed reflectometer. For exact description the error factor E_S has to be varied adaptive for each secondary reflection, i. e. each secondary reflection has to be modeled by a separate feedback loop. In what follows, the simplified signal flow graph representation is used to discuss the calibration procedure.

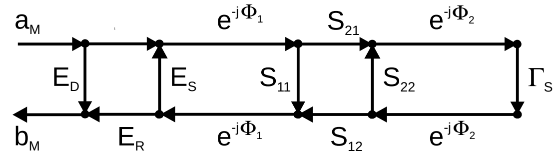

Figure 2: Simplified signal flow graph representation of the reflectometer.

For angles of incidence larger than seven degrees the waves reflected form the sample leave the measurement path, e. i. , $S_{11} = S_{22} = 0$. The system response of the reflectometer is given by

$$\Gamma^M(f) = E_D + \Gamma_0(f) + \Gamma_1(f) + \Gamma_2(f) + ... \quad (1)$$

E_D is the directivity factor and Γ_0 is the frequency response of the primary reflection. Γ_1 and Γ_2 are the frequency responses due to the first and the second parasitic reflection, respectively. The multiple reflections within the measurement path are caused by the source impedance factor E_S. Γ_0 is given by

$$\Gamma_0 = E_R e^{-j2\Phi_1} e^{-j2\Phi_2} S_{21}^2 \Gamma_S, \quad (2)$$

where S_{21} is the complex transmission coefficient of the planar sample, Γ_S is the reflection coefficient of the metal plate, E_R is the frequency response factor. The terms $e^{-j2\Phi_1}$, $e^{-j2\Phi_2}$ describe the phase shift due to the free-space between the lens and the sample and between the sample and the metal plate, respectively. The measurement plane for Γ_0 is located behind the lens. The calibration procedure of the reflectometer proceeds in four steps. In the first step, the unknown calibration coefficient E_D is determined from a measurement made with a matched load. The matched load is realized by inserting an absorber between the lens and the metal plate. The errors caused by the parasitic reflections are minimized by a mixed time/frequency domain method. In order to minimize the influence of second and higher order parasitic reflections on the measured data we have implemented a time domain gating technique. Truncation effects are avoided by using a relatively large window width. By the time domain gating procedure the spectra of the first parasitic multiple reflection is modified. Applying the first two steps of the calibration procedure the reflection coefficient becomes

$$\tilde{\Gamma}^M = \Gamma_R(f) E_R + \tilde{\Gamma}_1(f). \tag{3}$$

$\tilde{\Gamma}_1$ is the modified spectrum of the first parasitic reflection. In the third step, the influence of $\tilde{\Gamma}_1$ on the primary reflected signal is minimized: The reflection coefficient is measured for different positions of the metal plate. Subsequently the first two steps of the calibration procedure for each data set are applied and the equation

$$\begin{pmatrix} e^{-jk2\Delta d_1} & e^{-jk4\Delta d_1} \\ e^{-jk2\Delta d_2} & e^{-jk4\Delta d_2} \\ \vdots & \vdots \end{pmatrix} \begin{pmatrix} \Gamma_R E_R \\ \tilde{\Gamma}_1 \end{pmatrix} = \begin{pmatrix} \tilde{\Gamma}^M(\Delta d_1) \\ \tilde{\Gamma}^M(\Delta d_2) \\ \vdots \end{pmatrix}. \tag{4}$$

is solved. In the last step of the calibration procedure, the reflection response errors of the measurement set-up, the unknown reflection coefficient of the metal plate and the terms $e^{-j2\Phi_1}$, $e^{-j2\Phi_2}$ are eliminated by normalizing the reflection coefficient to amplitude and phase measured without a sample. The systematic errors of the reference measurement due to the directivity and the parasitic reflections are minimized by performing the first three steps of the calibration procedure. Normalization to the reference system response yields the square of the complex transmission coefficient of the investigated sample. An advantage of the normalization procedure is, that the measured square of the transmission coefficient is independent of the sample position and of the reflection coefficient of the metal plate.

RESULTS

In order to demonstrate the accuracy and the feasibility of the proposed calibration method we present the measured square of the complex transmission coefficient for a glass sample. The sample thickness is 1.893 mm. Fig. 3 shows the measured data for perpendicular polarization at the incidence angles 10°, 20°, 30° and 40°. Because of residual source mismatch, a ripple was observed in measured curves. With the proposed calibration procedure the magnitude and phase accuracy of the square of the complex transmission coefficient is better than ±0.003 and ±0.6°, respectively. In order to identify systematic measurement errors of the lens-focussed reflectometer we compare the measured square of complex transmission coefficient of the glass sample with data obtained

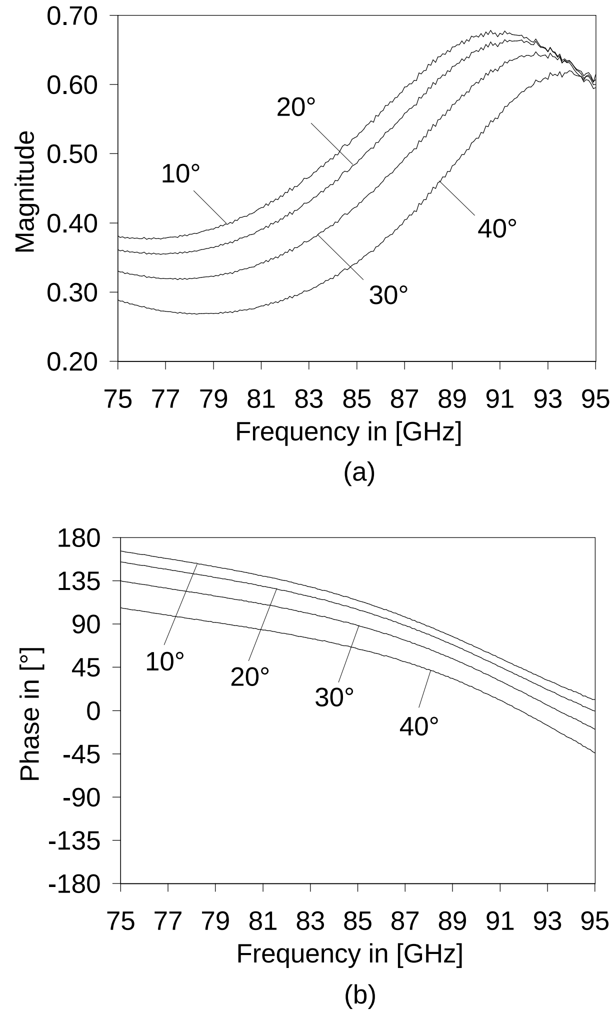

Figure 3: Measured square of the complex transmission coefficient of a glass sample with the sample thickness 1.893 mm: (a) magnitude and (b) phase.

with our optimized free-space transmission measurement system [5]. Fig. 4 shows the deviation in the magnitude and the phase of the two experimental curves. The deviation in the magnitude and in the phase is less than 1.0% and 1.0° for the entire frequency range from 75 GHz to 95 GHz, respectively.

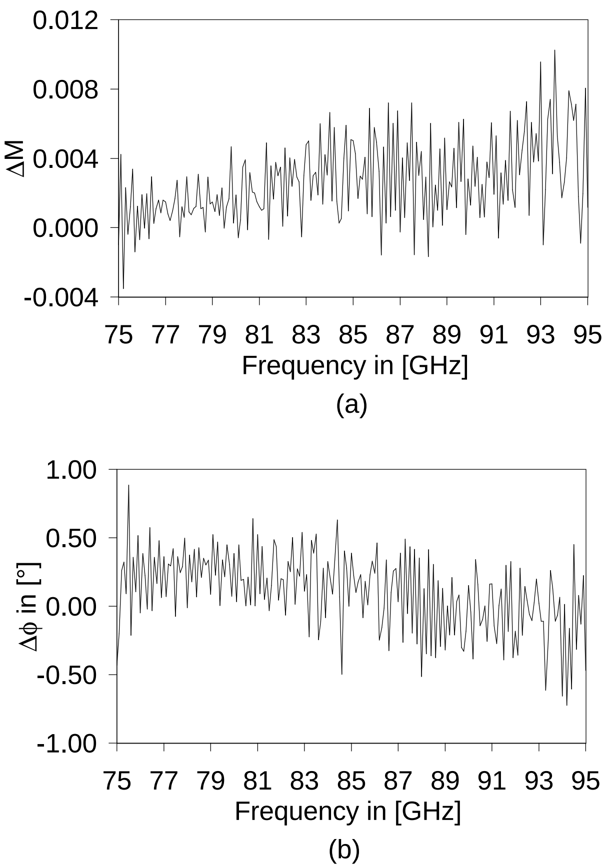

Figure 4: Deviation between the measured curves: (a) magnitude and (b) phase.

CONCLUSIONS

By use of a broad-band lens-focussed reflectometer the square of the complex transmission coefficient of planar samples is measured in the W-band. The calibration procedure covers the errors due to the non-ideal directivity and the parasitic reflections. The influence of the parasitic reflections on the measured data is minimized by means of a mixed time/frequency domain method. The feasibility of the proposed method has been verified by comparing the measured results with the square of the transmission coefficient determined with our free-space transmission measurement system. The deviation between the two measured curves is less than 1.0% in the magnitude and 1.0° in the phase.

ACKNOWLEDGEMENT

This work was supported by the "Deutsche Forschungsgemeinschaft" with the financial assistance of the "Bundesminsterium für Bildung, Wissenschaft, Forschung und Technologie".

REFERENCES

[1] J. Williams, "Accuracy Enhancement Fundamentals for Vector Network Analyzers ", *Microwave Journal*, pp. 99-114, March. 1989.

[2] D. R. Gagnon, "Highly Sensitive Measurements with a Lens-Focussed Reflectometer", *IEEE MTT Microwave Symposium*, pp. 1017-1018, 1991.

[3] U. Stumper, "Six-Port and Four-Port Reflectometers for Complex Permittivity Measurements at Submillimeter Wavelengths", *Transactions on Mivrowave Theory and Techniques*, Vol. MTT-37, pp. 222-230, No. 1, Jan. 1989.

[4] G. L. Friedsam, E. M. Biebl, "A Corrugated Horn Antenna for Gaussian Beam Optics at Millimeter Wavelengths" *Proceedings of PIERS 96*, pp. 620, July 1996.

[5] G. L. Friedsam, E. M. Biebl, "A Broadband Free-Space Dielectric Properties Measurement System at Millimeter Wavelengths", *IEEE Transactions on Instrumentation and Measurement*, Vol. 46, No 2, pp. 515-518, April 1997.