Precision Free-Space Measurements of Complex Permittivity of Polymers in the W-Band

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ABSTRACT

The complex permittivity of polymers used in millimeter wave systems has been determined by means of a broad-band free-space measurement system operating in the 75 GHz to 95 GHz frequency range. The technique is based on measurements of the complex transmission coefficient through planar samples for different angles of incidence and polarization states. Accurate estimates of the relative permittivity and loss tangent are obtained by employing an optimized measurement set-up and an enhanced processing of the measured data. The uncertainties of relative permittivity and loss tangent are as low as 0.1 % and 2×10^{-4}, respectively. Results are reported for nonpolar polymers (polypropylene, polyethylene, teflon, rexolite) and for polar polymers (nylon, plexiglas, PVC).

INTRODUCTION

In millimeter wave systems many kinds of polymers are used. Polymers are very easy to fabricate to any shape and size, exhibit relatively low loss, and are insensitive to adverse environmental conditions. For example, polymers are used as dielectric waveguides, substrate materials, mounts, windows and covers. Lenses made from polymers provide simple, low-cost beamshaping for radar systems in the millimeter wave range. But up to now the broad-band electrical behavior, i.e. complex permittivity, of the used polymers is only approximately known in the millimeter wave range. In [1] broad-band measurements based on dispersive Fourier transform technique from 50 – 300 GHz are reported. It is well known that this method exhibits sufficient accuracy only above 100 GHz [2]. Very accurate permittivity data is reported in [3], but only for a discrete frequency of 94 GHz. In the literature no accurate data of the continuous spectra of complex permittivity in the W-band has been reported. This is mainly due to the lack of a simple and accurate measurement system.

Millimeter waves are well above the frequency range where relaxation processes are observed. On the other hand the millimeter wave range is well below the resonance frequencies of intermolecular or latic vibrations. Thus, we may assume that the complex permittivity is nearly independent of frequency and use the permittivity values measured at lower frequencies for the design of simple millimeter wave devices. But for the design of critical parts of a millimeter wave system, like waveguides, substrates or lenses, we need accurate values of the permittivity and the dielectric loss in the millimeter wave range. Moreover, the dielectric loss tangent $\tan\delta_e$ of all polymers can vary markedly with the composition, history, and the temperature of the specimen. Thus, not only to acquire accurate data for the design, but to predict the variation of the millimeter wave systems behavior due to temperature and ageing we need a simple, accurate, and non-destructive measurement system to determine the complex permittivity.

In the millimeter wave range the complex permittivity of matter is mainly determined using open resonators [4], dielectric waveguide cavity resonators [5], or free-space techniques [3]. We found that the free-space techniques are best suited to meet our requirements: Admittedly, the open resonator method is most accurate. But a major disadvantage of this method is, that it is a discrete-frequency method. With dielectric wave-

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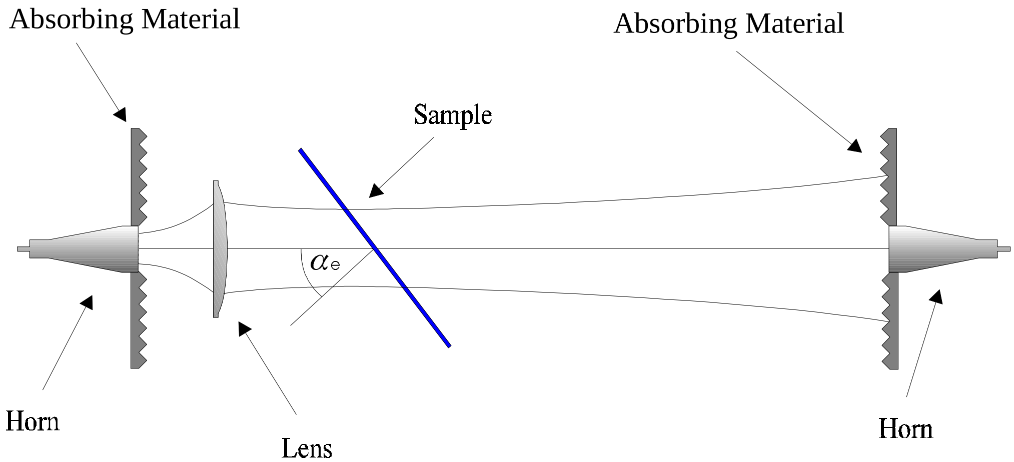

Fig. 1: Quasi-optical set-up for measuring the complex transmission coefficient.

guide cavity resonators good accuracy has been achieved. But the sample preparation is very expensive. Free-space techniques require only very little sample preparation. But the accuracy reported in the literature was not quite sufficient. Thus, we enhanced the measurement set-up and employed an optimized post-processing of the data measured in the frequency band from 75 GHz to 95 GHz to eliminate or at least reduce systematical and statistical errors.

In this paper, we present our optimized broadband free-space measurement system to determine the complex permittivity in the 75 GHz to 95 GHz range by measuring the transmission coefficient through planar samples for different angles of incidence and two polarisation states. We give permittivity data for polymers commonly used in millimeter wave systems like polypropylene, polyethylene, teflon, rexolite, nylon, plexiglas and PVC.

MEASUREMENT SET-UP

A schematic diagram of the quasi-optical measurement set-up is given in Fig. 1. The Gaussian beam excited by the transmitting corrugated horn antenna is collimated by means of a dielectric lens. By the collimated Gaussian beam a plane wave is approximated. In order to minimize the influences of the multiple reflections interaction between the dielectric sample and the receiving horn the distance between the lens and the receiving horn has been chosen relatively large. Errors due to diffraction effects at the edges of the sample are negligible, because the diameter of the investigated samples is larger than eight times the radius of the Gaussian beam at sample position. In order to avoid extraneous reflections into the measurement path, the area around the transmission path is covered with absorbing material. The sample holder is mounted on a precision motor driven rotary stage.

An automatic network analyzer HP8510 is used to analyze the received signals. Employing this set-up we measure the complex transmission coefficient of planar samples for different angles of incidence and for both perpendicular and parallel polarization in the 75 GHz to 95 GHz range.

PROCESSING OF MEASURED DATA

The frequency response errors of the measurement set-up are eliminated by normalizing the transmission coefficient to amplitude and phase measured without a sample in the transmission path. Using this calibration procedure the measured transmission coefficient is independent from the sample

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position. In order to minimize the errors caused by multiple reflections between the horn antennas and between the sample and the horn antennas, we have implemented a time domain gating technique. The large distance between the sample holder and the receiving horn effects, that the separation between the signal due to the direct transmission and those signals due to multiple reflections is relatively large in time domain. A second consequence of the optimized geometrical configuration is, that the amplitudes of the following signals are reduced. Using the time domain gating technique we reduced the uncertainty in amplitude and phase of the transmission coefficient to less than ±1% and ±0.5°, respectively.

The theoretical transmission coefficient for the measurement set-up can be described by the transmission coefficient of a plane electromagnetic wave through a infinite wide slab. We determine the mean value of the complex permittivity by fitting the theoretical model to the measured values of the complex transmission coefficient using a non-linear least-squares method. The error function is defined as

$$E = \sum_{i=1}^{N} |T^e_{t\,i} - T^e_{m\,i}|^2 + \sum_{i=1}^{N} |T^h_{t\,i} - T^h_{m\,i}|^2,$$

where $T^{e/h}_{t\,i}$ and $T^{e/h}_{m\,i}$ are the theoretical and measured transmission coefficient for the incidence angle $\alpha_{e\,i}$ and for the perpendicular or the parallel polarization, respectively. In contrast to most other methods we use a large data set to determine the complex permittivity. Numerical instabilities for low loss materials are avoided. Additionally this procedure yields an estimate of the standard deviation. The uncertainty analysis include the standard error of the estimate of the least-squares fit and the error caused by the uncertainty in the sample thickness. The confidence level is 67 %.

RESULTS

The presented method has been applied to polypropylene, polyethylene, teflon, rexolite, plexiglas, PVC and nylon. The sample thickness has been measured with a outside micrometer. The uncertainty in the sample thickness is ± 0.01 mm. Table 1 gives the measured sample thicknesses of the used samples. The diameter of all samples is larger than 300 mm.

Table 1: Sample Thicknesses

Matrial	Sample Thickness in [mm]
Polypropylene	41.83
Polyethylene	41.03
Teflon	9.05
Rexolite	17.96
Plexiglass	8.15
PVC	5.05
Nylon	19.85

For each sample the complex transmission coefficient has been measured at 41 different angles of incidence for the parallel and perpendicular polarization in the 75 GHz to 95 GHz range at 401 frequency points. In order to minimize the influence of the reflected wave from the sample and of the diffraction effects at the edges of the sample the measurements have been performed within the range $10° < |\alpha_e| < 50°$.

Table 2 shows the dielectric constants and the estimated measurement error at 76.5 GHz, 85 GHz and 94 GHz. Most millimeter wave devices and systems are realized at 76.5 GHz and 94 GHz allocated for automotive and IMS applications. For polypropylene, polyethylene, rexolite and nylon the standard deviation is less than 0.2% for ϵ_r and 2.0×10^{-4} for $\tan\delta_e$. For teflon, plexiglas and PVC the uncertainties are less than 0.2% for ϵ_r and 6.0×10^{-4} for $\tan\delta_e$. The measurement accuracy depends mainly on the sample preparation and the sample thickness. For accurate measurements the sample thickness normalized to the wavelength in the dielectric should be between 2 and 10.

Table 2: Dielectric constant at 76.5 GHz, 85 GHz and 94 GHz

Material	Estimates with Standard Error					
	76.5 GHz		85 GHz		94 GHz	
	ϵ_r	$10^3 \tan\delta_e$	ϵ_r	$10^3 \tan\delta_e$	ϵ_r	$10^3 \tan\delta_e$
Polypropylene	2.258 ± 0.002	0.61 ± 0.30	2.258 ± 0.002	0.56 ± 0.40	2.258 ± 0.002	0.57 ± 0.34
Polyethylene	2.307 ± 0.002	0.43 ± 0.11	2.306 ± 0.002	0.54 ± 0.12	2.306 ± 0.002	0.53 ± 0.13
Teflon	2.057 ± 0.004	0.83 ± 0.30	2.057 ± 0.004	0.78 ± 0.22	2.057 ± 0.004	0.72 ± 0.29
Rexolite	2.529 ± 0.002	0.63 ± 0.26	2.529 ± 0.002	0.72 ± 0.36	2.529 ± 0.002	0.69 ± 0.34
Plexiglas	2.592 ± 0.003	7.28 ± 0.43	2.591 ± 0.003	7.45 ± 0.41	2.590 ± 0.003	7.41 ± 0.29
PVC	2.740 ± 0.005	9.25 ± 0.52	2.738 ± 0.004	9.51 ± 0.38	2.738 ± 0.005	9.56 ± 0.33
Nylon	2.993 ± 0.002	8.17 ± 0.30	2.992 ± 0.002	8.37 ± 0.30	2.991 ± 0.002	8.36 ± 0.30

CONCLUSIONS

By use of a broad-band free-space measurement system the complex permittivity of common polymers has been measured in the W-band. The main source of systematic errors, namely multiple reflections within the measurement path, has been minimized by applying a time domain gating technique and by optimizing the geometrical configuration of the quasi-optical set-up. Mechanical and electrical measures have been taken to optimize the phase stability. Compared to the best results reported in the literature we achieved an improvement of the uncertainty of almost one order of magnitude. The standard deviation for dielectric constant and loss tangent measurements is less than $\pm 0.1\%$ and $\pm 2.0 \times 10^{-4}$, respectively. Supposedly these values give not only the uncertainty but the actual measurement error, since the remaining dominant systematic error source, namely the variation of the sample thickness, is already included in the values given above.

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REFERENCES

[1] M. N. Afsar, "Precision Millimeter-Wave Measurements of Complex Refractive Index, Complex Dielectric Permittivity, and Loss Tangent of Common Polymers", *IEEE Transactions on Instruments and Measurement*, Vol. IM-36, No. 2, pp. 530-536, Juny. 1987.

[2] M. N. Afsar, "Millimeter-Wave Dielectric Measurement ot Materials", *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-32, No. 12, pp. 1598-1609, July 1984.

[3] F. I. Shimabukuro, S. Lazar, M. R. Chernick, H .B. Howell, "A Quasi-Optical Method for Measuring the Complex Permittivity of Materials", *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-32, No. 7, pp. 659-665, July 1984.

[4] P. K. Cullen, "Measurement of permittivity by means of an open resonator", *Proceedings R. Soc. London*, A380, pp. 49-71, 1982.

[5] F. I. Shimabukuro, C. Yeh, " Attenuation Measurement of Very Low Loss Dielectric Waveguides by the Cavity Resonator Methode Applicable in the Millimeter/Submillimeter Wavelength Range", *IEEE Transactions on Microwave Theory and Techniques*, Vol. MTT-36, No. 7, pp. 1160-1166, July 1988.