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A Method for Determining the Dielectric Constant at Millimeter Wave Frequencies

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Abstract- **We present a straightforward method for determining dielectric constant of materials at millimeter wavelengths. By comparing the measured reflection coefficient phase change with the calculated phase change from a full wave simulator, we can accurately predict the dielectric constant of the material. For validation, simulation and measurement results are presented for fused quartz and for glass dielectric at W-band (75 – 110 GHz) frequencies with several lengths of quartz slab inserted into the waveguide.**

I. INTRODUCTION

The knowledge of the dielectric constant of materials is paramount for a millimeter wave design engineer. For example a design of a simple transmission line, microstrip or coplanar, is doomed to fail, if exact knowledge of the dielectric constant of the substrate material is not known.

Many materials are characterized at wide frequency range or their dielectric constant is nearly constant at microwave and millimeter wave frequencies (e.g., fused quartz), whereas many glass like and plastic materials have not been characterized, especially at millimeter wavelengths. Nevertheless, these materials can and sometimes must be used as a part of a support structure or even as a part of a millimeter wave system, e.g., as a support structure for a thin chip in on-wafer measurements or as a window material in applications, where waveguide or an antenna should be protected from outside atmosphere but otherwise operable.

Many methods have been envisaged for the evaluation and determination of the dielectric parameters of materials [1]-[3]. In this paper, we present one, which is fast, accurate and easy to use. The operation is based on the same principle as the waveguide backshort presented in [4], [5]. A piece of dielectric material is inserted into a waveguide and the resulting measured phase change caused by the material is compared to calculated phase change. We validate the method by measuring a slab made of known material, fused quartz, and then apply the method for determining the dielectric constant of unknown glass like material, used as a support structure on which other chips can be attached for on-wafer measurements.

II. ELECTRICAL AND MECHANICAL OPERATION

The operation principle of the method relies on the fact, that in a dielectrically loaded waveguide, the propagation constant is different compared to an empty waveguide. By inserting a piece of dielectric with known dimensions to a known position in a waveguide, we can determine the dielectric constant of the material by comparing the measured and calculated behavior of the electro-magnetic wave.

The measurement is done by first calibrating a network analyzer with waveguide heads. Then, a metal plate with standard flange interface is connected at the end of the analyzer waveguide, creating a short circuit. This is illustrated in Fig. 1. The metal plate has a narrow rectangular hole at the E-plane of the waveguide. The rectangular hole is narrow enough, so that it is still presenting a short for the waveguide. During the measurement, a slab of dielectric material is inserted into the waveguide through the rectangular hole, thus changing the reflection phase measured with the network analyzer. By comparing this phase change with full wave simulated phase change, the dielectric constant of the material can be extracted.

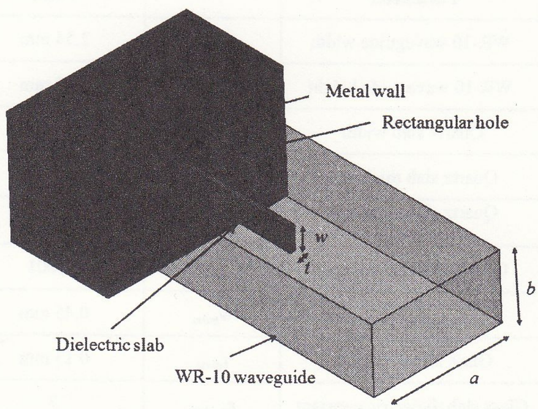

Fig. 1. 3D – illustration of a dielectric slab inserted into a waveguide.

It is important to control the volume of the dielectric material in the waveguide very accurately. In our case, the thickness and width of the dielectric slab are measured under the microscope and with a micrometer. The length of the dielectric slab in the waveguide is controlled with a micrometer positioning system shown in Fig. 2. The dielectric slab is attached to a steel slide, which is attached to a super magnet and finally the super magnet is connected to a micrometer head. The positioning can be done approximately with 10 μm accuracy.

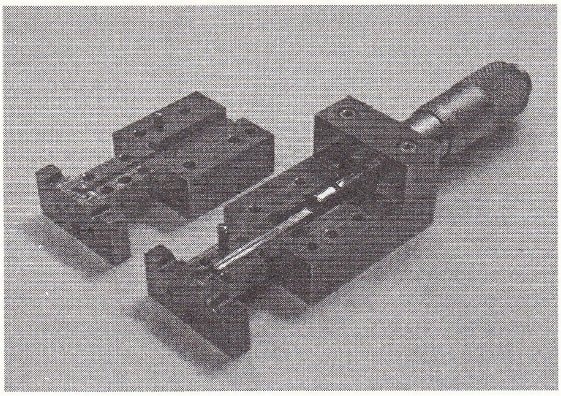

Fig. 2. Positioning system for the dielectric slab.

For the measurements, we use two different dielectric materials. First, we validate our method by measuring a slab made of fused quartz, which is a widely used material with known parameters up to THz frequencies. After the validation, we measure a dielectric slab made out of unknown glass-like material and determine its dielectric constant.

TABLE I
DIMENSIONS AND MATERIAL PARAMETERS

Parameter		Value
WR-10 waveguide width	w	2.54 mm
WR-10 waveguide height	h	1.27 mm
Quartz slab width	w_{quartz}	0.45 mm
Quartz slab thickness	t_{quartz}	0.1 mm
Quartz slab dielectric constant	$\varepsilon_{r,quartz}$	3.8
Quartz slab loss tangent	tan δ	0.0001
Glass slab width	w_{glass}	0.45 mm
Glass slab thickness	t_{glass}	0.13 mm
Glass slab dielectric constant	$\varepsilon_{r,\,glass}$	?
Glass slab loss tangent	tan δ	?

All the measurements are done in WR-10 waveguide environment. The material parameters and dimensions used for the extraction are given in Table 1.

III. MEASUREMENT AND SIMULATION RESULTS

Measurements are done with HP 8510 Network analyzer. A two-port thru-reflect-line calibration (TRL) was performed before the measurements using HP WR-10 Calibration Kit W1164A. The results are for the port, where the dielectric slab positioning system was attached. In the measurements of the quartz slab, the slab was moved 0…8 mm inside the waveguide with 0.5 mm steps and in the measurements of the glass slab, it was moved 0…7 mm into the waveguide with 1.0 mm steps.

The simulations are done with Ansoft High Frequency Structure Simulator (HFSS). The parameters given in Table 1 are used for the dielectric material and for the waveguide. In addition, a metal conductivity of 1.5×10^{7} S/m (brass) was used for the positioning system and the conductivity of 4.1×10^{7} S/m (gold) was used for the waveguides. Metal surface roughness of 0.2 μm was used for all metal surfaces. In the simulations of both, the quartz slab and the glass slab, the slab was moved into the waveguide with 0.1 mm steps.

The reflection coefficient phase change as a function of the quartz slab length in the waveguide at 75 GHz, 92.5 GHz and 110 GHz is shown in Figs. 3-5. It can be seen that the assumed dielectric constant of the quartz, $\varepsilon_r = 3.8$, results in a very good match of measurements and simulations.

After the validation of the method with the fused quartz as the dielectric material, we did measurements for the unknown "glass-like" material. After several iterations of the dielectric constant, the best match between measurements and simulations was found with the dielectric constant, $\varepsilon_r = 7.0$. The results for this dielectric constant value are shown in Figs. 6-8. In Fig. 9, a ±10 percent change in the dielectric constant of the glass-material at 92.5 GHz is illustrated. It can be seen that the accuracy in determining the dielectric constant with this method is easily within ±10 percent. The method is more accurate with increasing the length of the dielectric in the waveguide.

IV. LOSSES AND DETERMINATION OF THE LOSS TANGENT

Our method is not feasible for the exact determination of the loss tangent for low loss materials such as quartz. For example, in our case, the return loss for quartz slab is less 0.12 dB over the frequency band of 75 – 110 GHz. These losses are of the same order as measurement uncertainty and thus the determination of the loss tangent would not be reliable.

However, for materials with higher losses, an estimate of the loss tangent can be extracted by comparing the simulated and measured reflected power. This is illustrated in Fig. 10, where measured return loss is shown with simulated return losses for loss tangent values of 0.025, 0.03, and 0.035, respectively. It can be seen from the figure, that an average loss tangent value of 0.03 would be good estimate over the W-band. Furthermore, the results indicate that the loss tangent is slightly increasing with frequency.

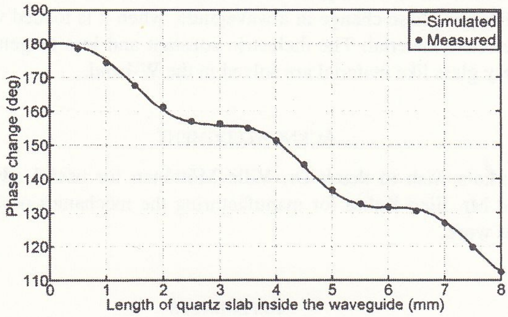

Fig. 3. Phase change in the reflection coefficient at 75 GHz when fused quartz slab is inserted in the waveguide. Dielectric constant of 3.8 is used for the fused quartz.

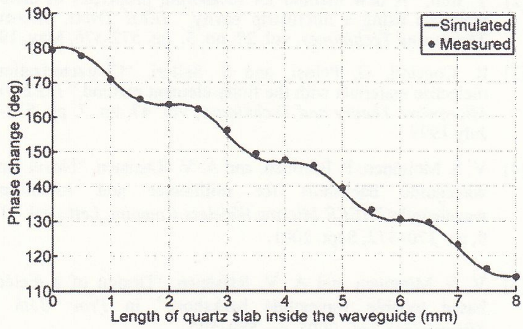

Fig. 4. Phase change in the reflection coefficient at 92.5 GHz when fused quartz slab is inserted in the waveguide. Dielectric constant of 3.8 is used for the fused quartz.

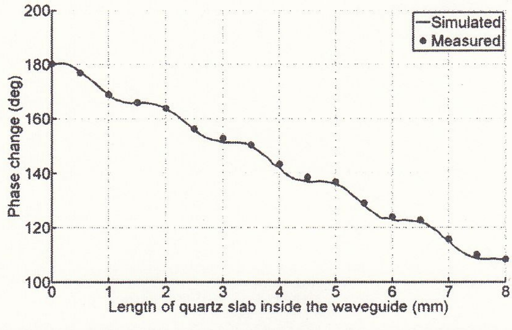

Fig. 5. Phase change in the reflection coefficient at 110 GHz when fused quartz slab is inserted in the waveguide. Dielectric constant of 3.8 is used for the fused quartz.

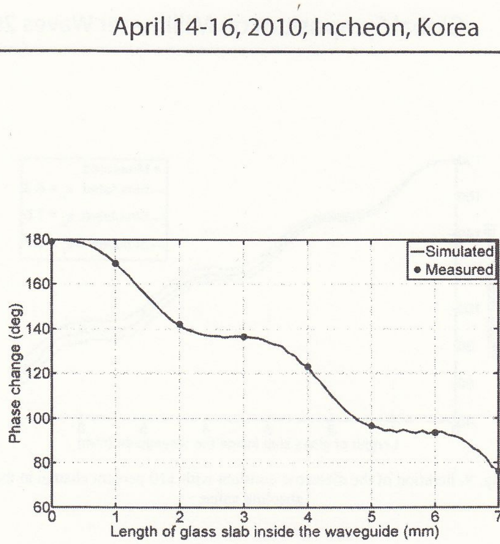

Fig. 6. Phase change in the reflection coefficient at 75 GHz when "glass" material slab is inserted in the waveguide. Dielectric constant of 7.0 is used for the "glass" material.

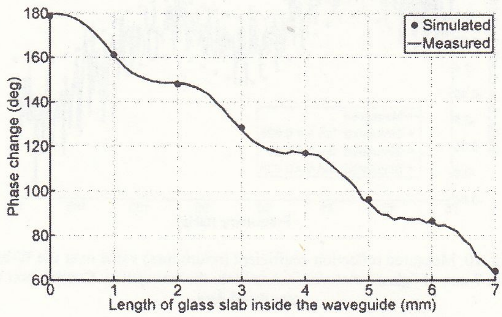

Fig. 7. Phase change in the reflection coefficient at 92.5 GHz when "glass" material slab is inserted in the waveguide. Dielectric constant of 7.0 is used for the "glass" material.

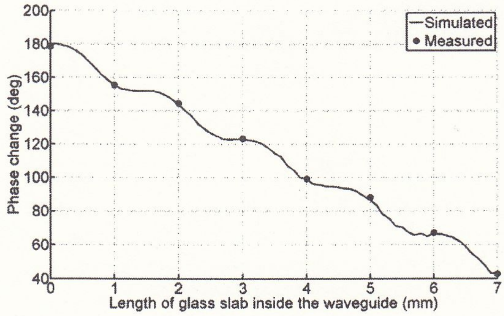

Fig. 8. Phase change in the reflection coefficient at 110 GHz when "glass" material slab is inserted in the waveguide. Dielectric constant of 7.0 is used for the "glass" material

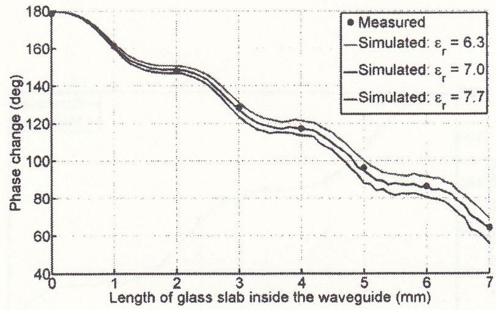

Fig. 9. Iteration of the dielectric constant with ±10 percent change in the absolute value.

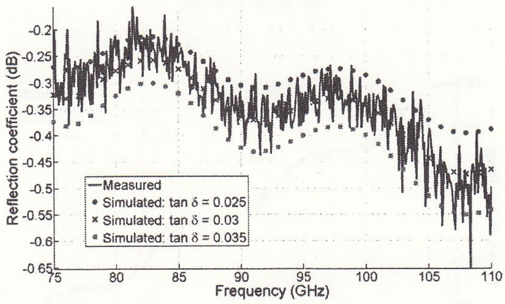

Fig. 10. Measured reflection coefficient (return loss) value over the W-band with 7 mm of "glass" material inserted into the waveguide. Comparison with simulated data.

Conclusions

A simple method for determining the dielectric constant of materials at millimeter wavelengths is presented. The method is based on the comparison of the measured and simulated reflection phase change in a waveguide, when it is loaded with dielectric material. The dielectric constant and loss tangent of lossy glass like material are solved in the W-band.

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