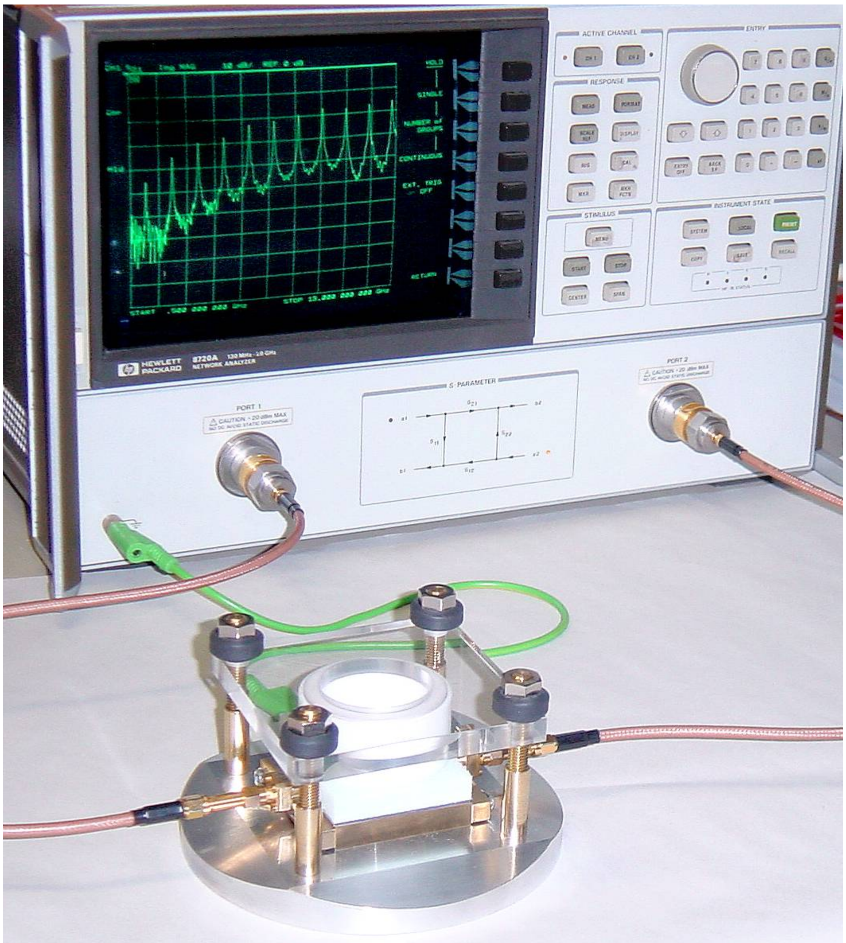

Substrate Measurement System (SMS):

Resonance-based electromagnetic measurement of planar dielectrics

User Manual Of Version 6.0

Manual version: 2014 August

Substrate Measurement System (SMS)

All parts of the software, the documentation and the measurement setup have been designed very carefully and have been tested for correctness.

All information in this documentation, the associated software and the measurement setup may be modified at each time without special notice to follow technical progress.

Heuermann HF-Technik GmbH is not responsible for any damages in conjunction with the usage of the Substrate Measurement System.

Heuermann HF-Technik GmbH is henceforth in this document also referred to as HHFT GmbH.

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Heuermann HF-Technik GmbH
Jülicher Straße 236
D-52070 Aachen
Germany

Tel.: +49 241 95451312
FAX: +49 2408 9379952
E-Mail: Info@HHFT.de
website: http://www.hhft.de

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1. Introduction

This introduction describes the *Substrate Measurement System (SMS)* as developed by HHFT GmbH. The system is suitable to characterize uncoated dielectric probes using microstrip resonators. It is available in various options, shown in Tab. 1.a.

Option	Range of probe thickness	Range of rel. permittivity	Frequency range
Standard	ca. 0.5mm - 1.5mm	ca. 2 - 6	ca. 1GHz - 13GHz
UHF	ca. 0.5mm - 1.5mm	ca. 2 - 6	ca. 0.7GHz - 6GHz
UHF thin	ca. 0.03mm - 0.5mm	ca. 2 - 6	ca. 0.7GHz - 6GHz

Tab. 1.a: Overview of available options

To perform measurements, a two-port vector network analyzer with coaxial measurement cables (SMA connectors) is required, as well as a PC with a Windows operating system to run the evaluation software. To perform automated measurements, a National Instruments or Agilent PCI-GPIB controller card and a GPIB cable to the vector network analyzer are required. The tested compatible combinations of hardware and operating system are found in Tab 1.b.

Operating system	Computer's communication hardware	VNAs tested and found to be compatible	VNAs likely to be compatible
Windows Vista. (Windows XP or Windows 7 likely compatible.)	Agilent GPIB PCI card. National Instruments USB to GPIB connector.	Rohde & Schwarz ZVA50.	Rohde & Schwarz ZVA-series with at least a 1 GHz - 13 GHz range.
Windows Vista. (Windows XP or Windows 7 likely compatible.)	National Instruments GPIB PCI card.	Agilent 8510C.	Agilent 8510-series (8510X-series). Agilent 8720-series (872X-series).

Tab. 1.b: Compatible hardware and operating system combinations. A row represents a compatible combination.

The mechanical setup and the software handling will be described in the following chapters.

2. Mechanical setup

2.1 Components

The assembled test fixture is shown in Figs. 1 and 2.

Fig. 1: Test fixture with base plate, SMA coupling elements and pressure block

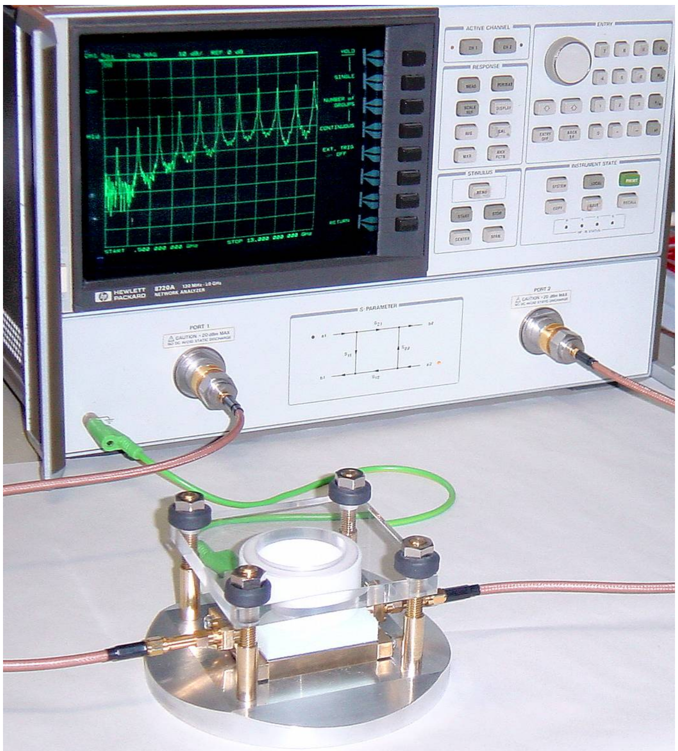


Fig. 2: Measurement setup with VNA connected and displayed frequency response

Fig. 3 shows the different components of the Standard SMS.

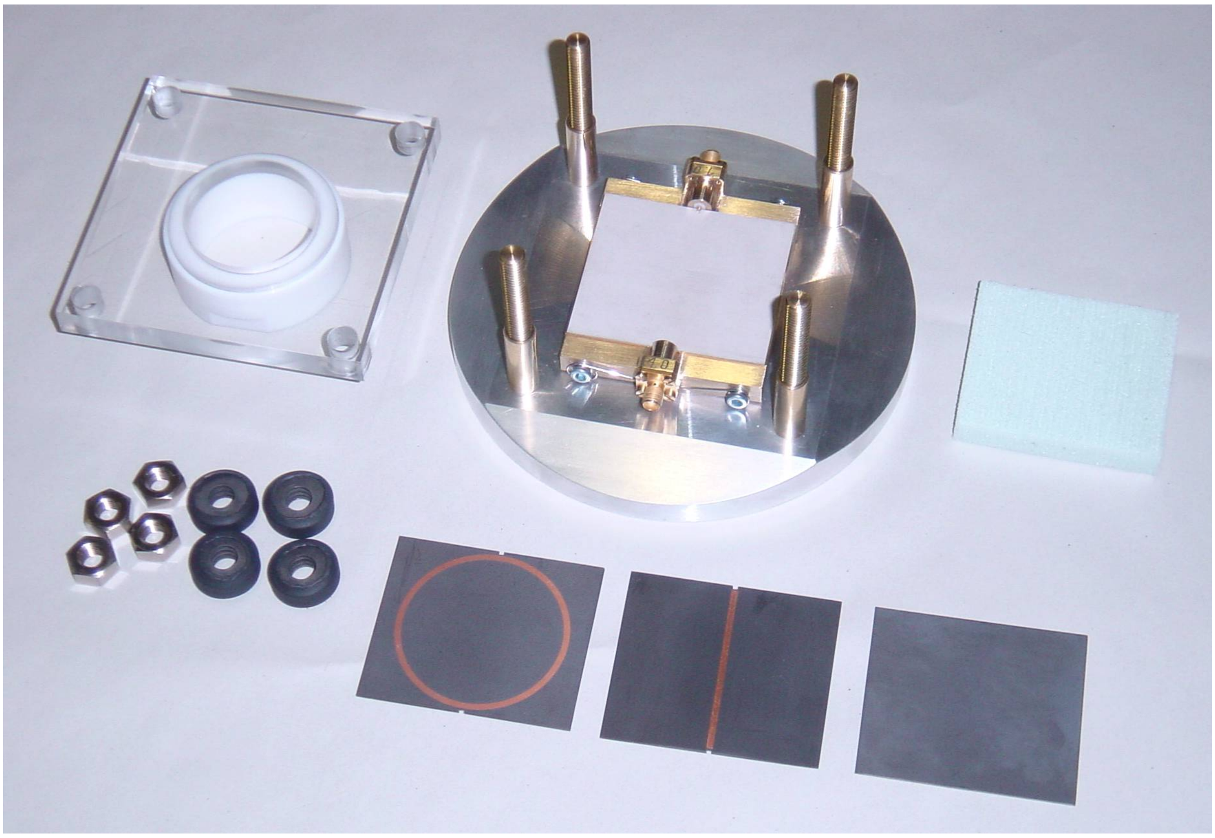


Fig. 3: Components of SMS

The hardware consists of an aluminum base plate with applied brass block and four columns (in Fig. 3). In Fig. 3 an example of a planar dielectric to be measured is placed on the brass block. The SMA coupling elements have to be mounted at opposite sides of the brass block. The four columns are required to fix the pressure block, consisting of a Styrodur block, a white Teflon ring and a plexiglas plate.

The bottom row of components in Fig.3 shows the fixing nuts and the plate springs as well as the various boards (board with ring, board with straight resonator and verification/calibration board).

An overview of the available boards is given in Tab. 2.

Option	Supplied boards and coupling elements	Denotation
Standard	Ring resonator with two notches Straight resonator with two notches Unmetalized system verification/calibration board Two coupling elements with 0.7mm pin length Two coupling elements with 1.0mm pin length	STD1 STD2 CAL2 AK07 AK10
UHF	Butterfly resonator with two notches Unmetalized system verification/calibration board Two coupling elements with 1.5mm pin length	UHF1 CAL2 AK15
UHF thin	Butterfly resonator with surface contact Butterfly resonator with surface contact Unmetalized system verification/calibration board Two coupling elements with 1.5mm pin length	UHF2 UHF3 CAL2 AK15

Tab. 2: Supplied boards for the various options

The boards consist of low-loss Rogers laminates.

2.2 Assembly

To characterize a planar dielectric, it first has to be cut to a board with a size of approx. 56 mm x 64 mm and placed on the brass block. This board will henceforth be referred to as the board to be measured or BTBM.

Depending on the BTBM's thickness and permittivity, the resonator board and the coupling elements have to be selected. The goal here is to obtain a coupling strength such that the amplitudes of the resonances are between about -50dB and about -15dB in the complete frequency range. Tab. 3 and 4 give some hints. In some cases, simply a quick overview measurement shows whether the board and/or the coupling elements are ok or have to be exchanged.

Please note, that the definite chosen resonator board has to be specified in the Preferences window of the processing software (see chapter 5).

Rel. eps_r	Thickness of board to be measured 0.5 - 1.0mm	1.0 - 1.5mm
2 - 6	STD1 or STD2 AK10	STD1 or STD2 AK07

Tab. 3: Use of resonator board and coupling elements for the Standard option.

Rel. eps_r	Thickness of board to be measured			
	0.03 - 0.15mm	0.15 - 0.35mm	0.35 - 0.5mm	0.5 - 1.5mm
2 - 4	UHF3 AK15	UHF2 AK15	UHF2 AK15	UHF1 AK15
5 - 6	UHF3 AK15	UHF3 AK15	UHF2 AK15	UHF1 AK15

Tab. 4: Use of resonator board and coupling elements for UHF option

For resonator boards with notches, first mount two SMA coupling elements at the brass blocks so that their pins touch the top surface of the BTBM. Then place one of the resonator boards (with the etched resonator facing downwards) on the probe so that both coupling pins will lie within the notches of the resonator board.

For resonator boards without notches, first place the resonator board (with the etched resonator facing downwards) on the BTBM. Then mount the coupling elements at the brass block so that their pins touch the surface contact on the resonator board.

After this has been accomplished, place the Styrodur block, the Teflon ring and the Plexiglas plate on the resonator board, add the plate springs and the nuts to the columns. The four nuts should first be screwed on until a certain resistance occurs. Then, diagonal nuts should be tightened by about ¾ of a turn. and tighten the nuts to reach a certain mechanical tension.

During all steps, be cautious that there are no small particles on the surfaces of the applied parts.

Use the 4 mm jack in the aluminum base plate to ground the setup by connecting it to the ground jack of the VNA.

Now, the setup is complete to characterize a BTBM using the evaluation software as described in the following.

After measurements are completed, it is recommended to dismantle the setup.

3. Installation of the software

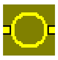
To install the evaluation software, just copy the directory SMS from the CD ROM into any directory of the hard disk (e.g. *c:\program files\sms*).

The software requires a dongle. Normally, the dongle does not require any driver installation and it will be detected by the system upon first insertion in a USB port.

The installation of a driver for a National Instruments or Agilent GPIB controller card (to perform automated measurements) is described in the documentation of that card.

The software requires that the Agilent "IO Libraries Suite" is installed. Agilent recently split itself into 2 companies, the electronic measurement division of Agilent is now a company on its own and is known as Keysight. Thus the required "IO Libraries Suite" is now freely available from the Keysight website. Also, this 'library suite' is variously referred to as "Agilent IO Libraries Suite" or "Keysight IO Libraries Suite".

4. Starting the software

Click the SMS icon  to start the software. The SMS startup window appears.

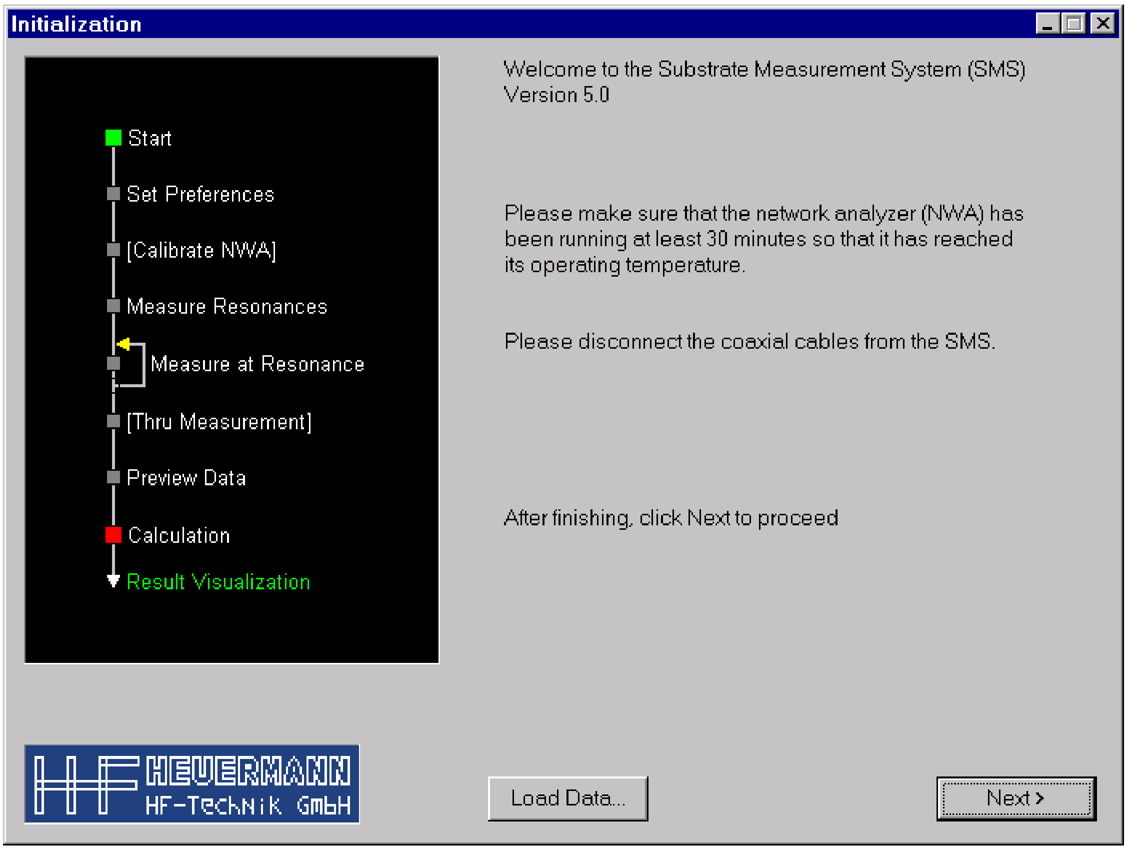


Fig. 4: Startup window

The graphic at the left part of the window is a flow-chart-like guide that leads you through the program and the measurement procedure. A green box indicates the currently active step in the measurement process.

The buttons labeled *Next* and *Previous* are used to navigate within the program and can also be found in the following windows.

The *Load Data...* button is used for the verification of previously performed measurements, which is explained in more detail in the chapter “Loading previously stored files”.

The startup window also gives a reminder that the vector network analyzer (VNA) should run at least 30 minutes (warm-up time) before the measurements can be started. In this stage (and also for a possibly following VNA calibration) all coaxial cables should be disconnected between VNA and SMS.

Click the *Next* button to proceed to the next window.

5. Preferences

The second window is used to define preferences and characteristics of the measurement.

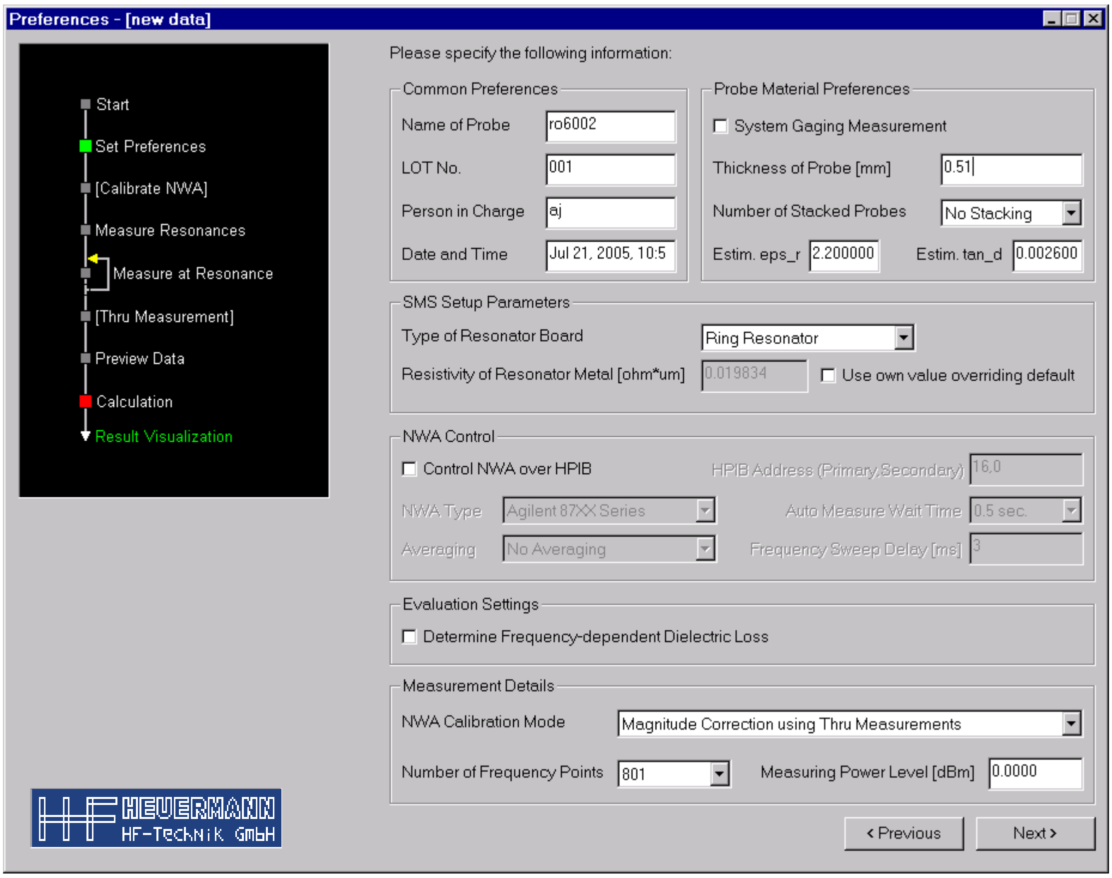


Fig. 5: Preferences

Through-out the software the BTBM is referred to as 'probe' and a VNA is referred to as a NWA.

Most entries of this window are self-explanatory. The probe name, the LOT no. the name of the person in charge and the date can be chosen arbitrarily.

It is important to specify the properties of the probe (BTBM) correctly: Thickness and estimations for expected ε_r and tan δ. The possibilities of the calibration measurement (system gaging) will be explained later.

It is important to specify the correct resonator board type. In general, the settings for the specific resistivity of the resonator metallization should not be modified (as it belongs directly to the test fixture or can be specified using the system calibration, respectively).

To use automated measurements, select the box in the *VNA Control* field. It is then necessary to specify the VNA-model, its HPIB address, the waiting time after each detailed resonance measurement (increase time if you want to watch the resonance curve for a while) and the speed of a frequency sweep in ms per frequency point (increase time if your VNA / PC communication requires this). For every VNA model other than the 'Agilent 87XX Series' or 'Agilent 85XX Series' these last 2 settings generally do not have to be changed.

In *Measurement Details,* settings of the measurement procedure are set. **The most important one is the choice between “Magnitude Correction using Thru Measurements” and “Measurement using Full NWA calibration”.**

In “Magnitude Correction using Thru Measurements”, the resonance behavior is measured without VNA calibration and only at the end an amplitude correction is undertaken using thru measurements. This is ok, if in a typical 3dB frequency span the thru measurement shows no considerable frequency variations.

In “Measurement using Full NWA calibration”, in the beginning a broadband calibration of the VNA is undertaken and, if the VNA allows it, the narrow band resonance behavior measured using the broadband calibration. If the VNA does not allow this, a new VNA calibration has to be made for every narrow band resonance measurement.

Click *Next* to proceed to the next window.

6. Broadband VNA calibration

Through-out the software a VNA is referred to as a NWA.

If in the “Measurement Details” the mode “Measurement using full NWA calibration” was selected, then the user is now asked to perform a broadband calibration of the VNA.

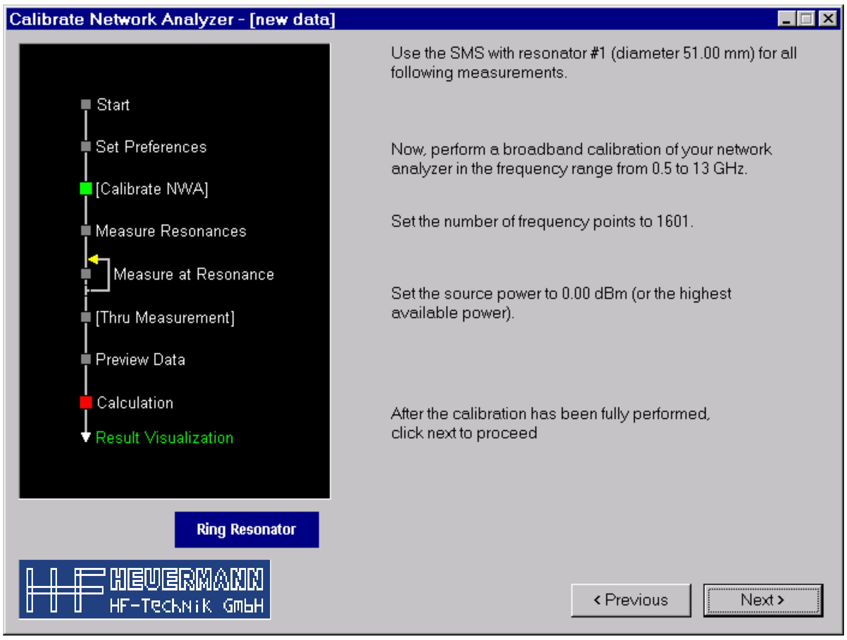


Fig. 6: Broadband VNA calibration

After the VNA calibration has been completed, click *Next* to go to the next window. There are 2 possibilities, depending if “Control NWA over HPIB” was chosen or not in the Preferences window. The case that it wasn't chosen is explained in chapter 7 “Manual recording of resonance frequencies”. The case where it was indeed chosen is explained in chapter 8 “Automated recording of resonance frequencies”.

7. Manual recording of resonance frequencies

Now, the SMS test fixture has to be connected to the VNA. The VNA display needs to be set to transmission (S_{21}).

The displayed resonance frequencies need to be entered into the list field. Each resonance has to be entered into the text box, followed by a click on *Add*. The resonances will be automatically sorted. It is also possible to add each second resonance only, e.g., or to leave out poor measurements. The resonance order will be detected automatically. To have this function work properly, it is essential that the frequency of the first order resonance (fundamental harmonic) is entered first.

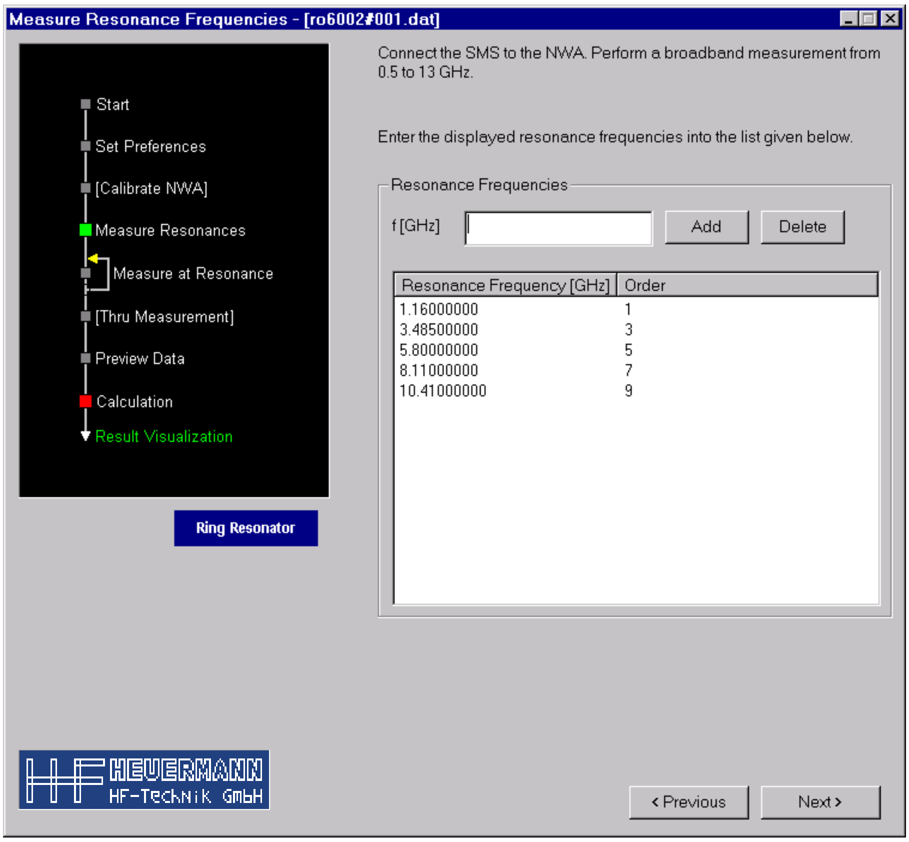


Fig. 7: Entering resonance frequencies

Use *Delete* to remove a previously entered frequency from the list.

After all resonances have been entered, click *Next* to proceed to the next window which is further explained in chapter 9 “Manual recording of measurement results”.

8. Automated recording of resonance frequencies

After connection of the SMS test fixture to the VNA, the SMS software will configure the VNA so that a broadband measurement is performed and the characteristic resonance display appears on the VNA screen. The measurement results will be transferred to the software which will automatically detect the resonance frequencies and display them in a list. Clicking next will bring you to the step explained in Chapter 10 “Automated recording of measurement results”.

9. Manual recording of measurement results

In this step the software will guide you through the narrow band measurements it needs. It will ask you to perform in the given frequency range (around the currently active resonance) a narrow band measurement of the transmission. The VNA must be configured in such a way that the absolute value of the transmission ($|S_{21}|$) is displayed in dB.

From this display, the maximum value of $|S_{21}|$ in dB has to be determined, as well as the exact appropriate resonance frequency in GHz. Both values have to be entered into the respective text boxes. Furthermore, use the VNA display (visual read-out) to determine the 3 dB bandwidth in MHz and enter this value into the respective text box. In case the VNA supports the automatic detection of the 3 dB bandwidth using markers the use of this function is recommended to make the determination of the measurement results easier or more accurate.

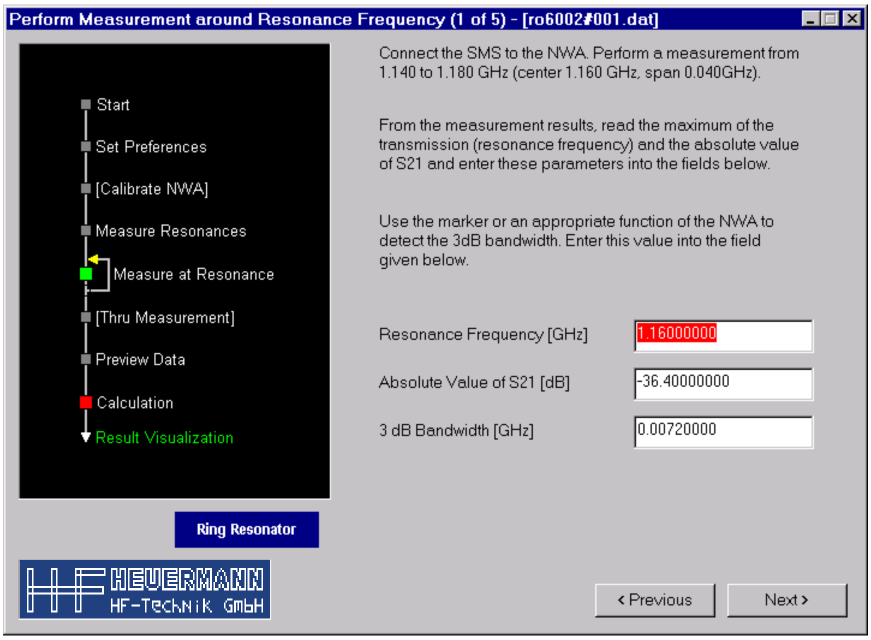


Fig. 8: Entering measurement results

After all measurement results have been determined and entered, click *Next* to proceed to the next window.

As long as not all resonances have been measured in a narrow band, clicking *Next* leads back to the same type of window as described in this chapter. Notice the iterating arrow in the flow-chart-like guide in Fig.8. After having entered all results for detected and relevant resonances clicking *Next* proceeds to the calculation window. The title bar of the window indicates how many narrow band measurements have been performed so far (for example, in Fig.8 the first out of 5 is being preformed).

10. Automated recording of measurement results

In case of automated measurements the SMS software configures the connected VNA so that each single resonance will be measured with a high resolution to optimally detect the 3 dB bandwidth.

The software then automatically receives the frequency of the maximum transmission, the respective amplitude in dB and the 3 dB bandwidth and displays these values in the appropriate fields of the window as given in Fig. 8. Before proceeding to the next measurement, the software will wait for a time period or a click on the “Next>”-button as specified in the Preferences window.

11. Thru measurement for amplitude correction

If the “Measurement Details” mode “Magnitude Correction using Thru Measurements” was chosen, the user is now asked to perform measurements on a thru element.

Disconnect the SMA connectors from the SMS test fixture and connect them to a thru element.

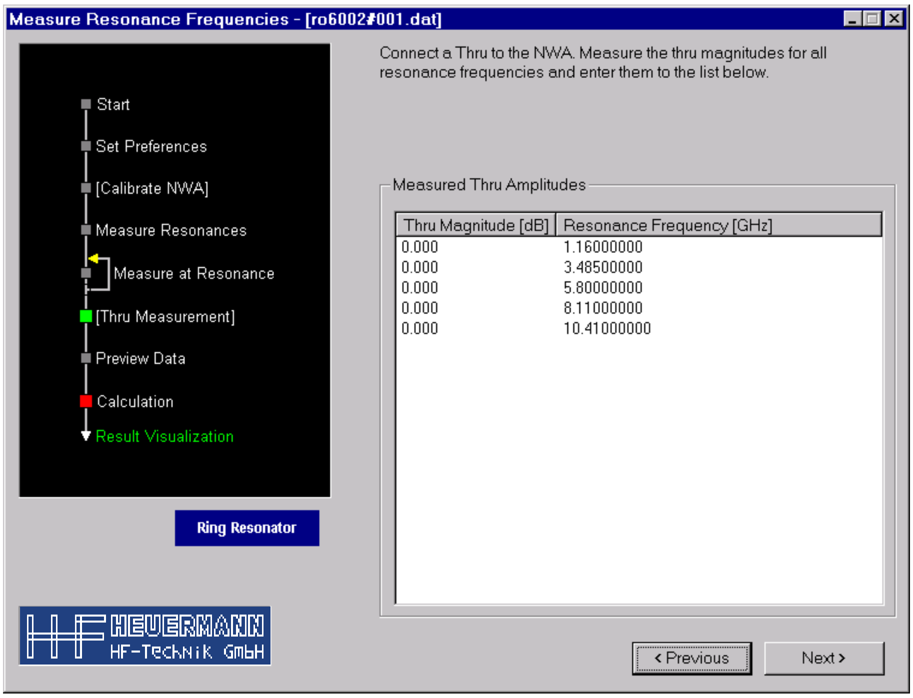


Abb. 9: Thru measurement

Ideally the values for the Thru would be 0dB, a result which would not require any correction of the previously measured resonance amplitudes. In reality, values different from 0dB will result and have to be entered in the list. For that, please click on the 0.000 so that it gets red and can be modified. However if “Control NWA over HPIB” was chosen in the Preferences window these measurements are executed automatically by clicking the “Next>”-button (don't forget to connect the thru element first).

12. Controlling measurement results

This step gives the possibility of checking the entered measurements and to eliminate poor measurements from the following calculations, if necessary.

In the window corresponding to this step the values for the attenuation α and the dielectric constant ε_r (as derived from the measurement results) are displayed versus frequency.

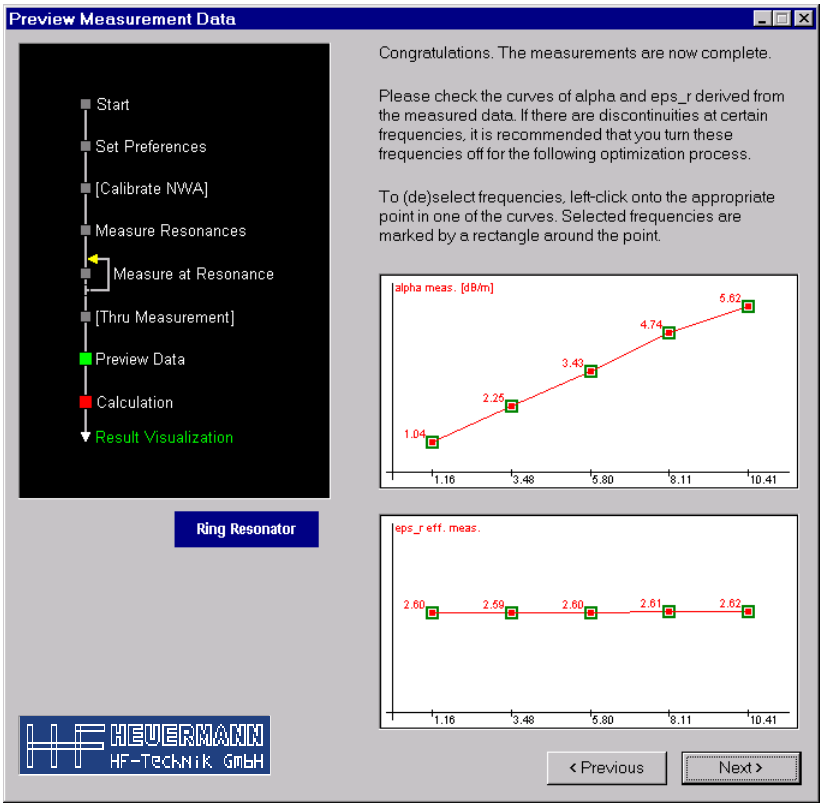


Fig. 10: Controlling measurement results

To deselect a frequency so it won't be used in all further calculations, left click it in one of the diagrams. The green marker will turn off to indicate that the frequency is deselected. To re-select a frequency again, left click it once more.

It is not possible to deselect the fundamental frequency.

13. Performing calculation

During this step the calculation of the material properties is preformed. The value of ε_r will be calculated separately for each frequency, while for the dielectric loss (characterized by tan δ) a single value will be calculated, taking all frequencies into account.

The calculation may take some minutes, depending on the number of resonances, the quality of the measurement results and the system speed.

The progress in determining the material properties will be indicated by corresponding messages. Additionally there is a graphical display of the measured and calculated $\varepsilon_{r,eff}$ (for the calculation of the dielectric constant), the measured and calculated attenuation α (for the calculation of the dielectric loss and for the calibration).

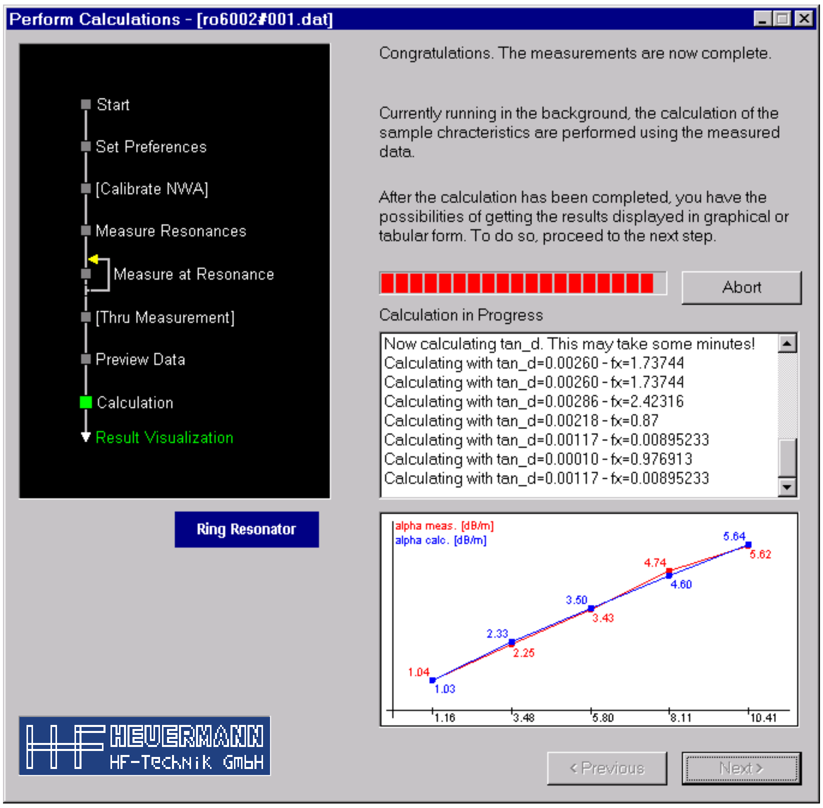


Fig. 11: Performing the calculation

To cancel the calculation, click the “Abort” button. It is possible to then use the “<Previous”-button to check and control previously entered values before restarting the calculations.

After all calculations have been completed, click *Next* to proceed to the following window.

14. Results visualization

This is the final step, it provides visualization capabilities for the previously calculated results. The display can be done in both graphical (*Graph*) and tabular (*Table*) form. The displayed graphic or table can be printed using *Print* and can be copied to the Windows clipboard using *Clipboard Copy*. Allowing one, for example, to further process the results to generate a comprehensive report using an office suite like LibreOffice.

To start *LINMIC Interconnect* click onto the respective button and an adequate substrate configuration is loaded, in analogy with the configuration used for measurements and evaluation. A recalculation and control of the previously calculated results can thus be done easily, as well as modifications and simulations of strip structures.

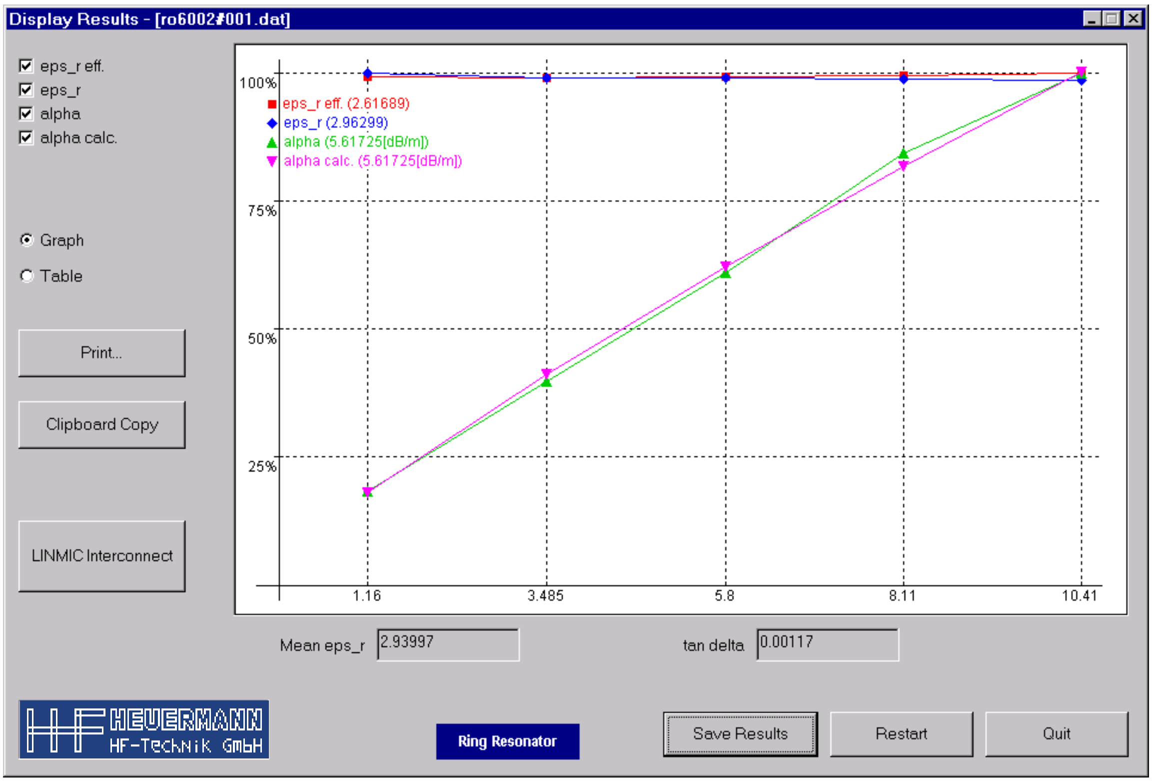


Fig. 12: Results visualization

Click *Save Results* to save the results into a text file (extension .dat) which can be loaded by this software to verify a previously performed measurement, e. g. It is also possible to save the results into a .csv file. This file format is suitable for directly post-processing the data in a spreadsheet program such as LibreOffice's Calc.

Click *Quit* to leave the program (don't forget to save useful results first).

15. Loading previously stored files

As already mentioned it is possible to reload previously stored simulation results. Make use of the *Load Data* button in the start window. After selecting a file, a window appears, providing an overview of the loaded data.

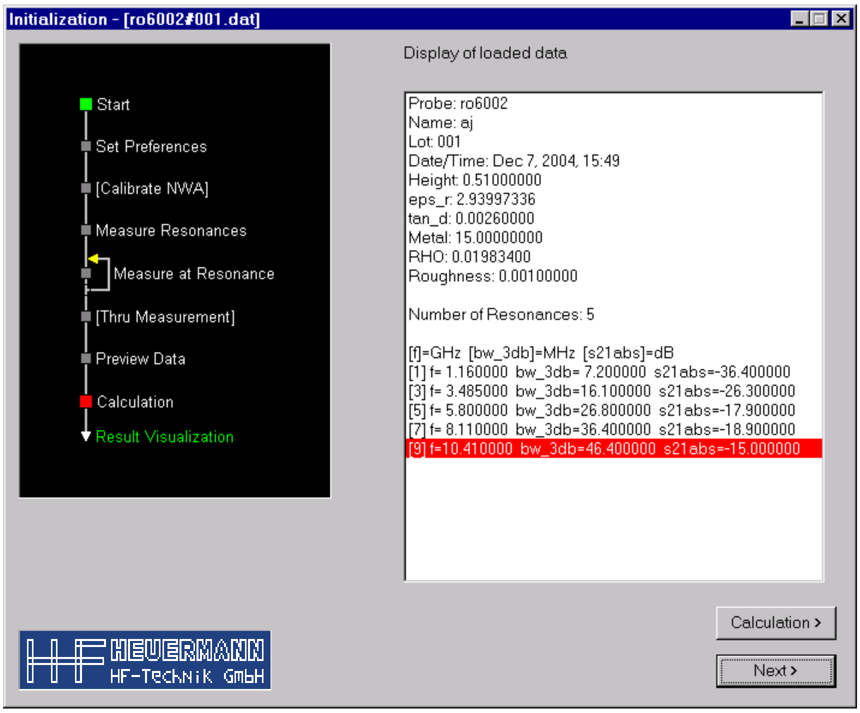


Fig. 13: Loaded data

You can choose now among direct calculation (*Calculation*) or running through the usual window order (*Next*). In the latter case, all input fields will be preset with the loaded values, thus providing the possibility of changing certain measurement values and controlling how the results become affected.

16. System verification and calibration

To verify the stability of the system, it is useful to measure a constant substrate (for example the verification/calibration substrate supplied with the system) from time to time and compare the results.

Experience shows that the properties of the SMS test fixture are nearly constant over time compared to its first use.

However when noticeable changes are observed, the changed system behavior can be compensated for in the software. For that, please activate the “System Gaging Measurement”-mode in the Preferences window.

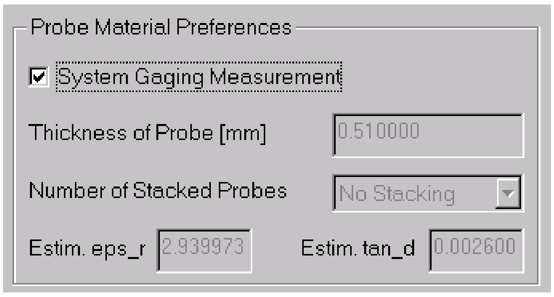


Fig. 14: Activate system gaging

In this mode, the supplied verification/calibration substrate is measured. In this measurement procedure the verification/calibration substrate's eps_r and tan_delta are not determined, but considered as known and instead the specific resistance of the system is determined and, if desired, stored as a parameter for all following measurements.

In the following program windows it is now indicated that the program is running in gaging mode.

17. Short description of LINMIC Interconnect

LINMIC Interconnect was a product of AC Microwave GmbH and is not sold by HHFT GmbH, however if you are interested in LINMIC Interconnect we can supply you with contact information. A short description of LINMIC Interconnect by AC Microwave GmbH is given below:

LINMIC Interconnect is a tool for the simulation of single and coupled strip lines in a single or multilayer substrate. It contains two simulators:

- CAPIND2D is a 2D quasi-TEM Simulator, taking into account dielectric and metal losses and finite metallization thicknesses, but no dispersion. CAPIND2D is suitable for up to 20 dielectric layers with up to 19 metal layers.

- MMICTL is a 2D full wave simulator, taking into account dielectric and metal losses and dispersion, but no finite metallization thicknesses. MMICTL is suitable for for up to 6 dielectric layers with up to 2 metal layers.

After the installation has been done, only three steps are necessary to use one of the simulators:

1. Start LINGRED and select the simulator in the *Simulators* menu. After that, enter the desired substrate configuration and strip structure. For a fast and convenient work, use the assistant from the *Circuit* menu.

2. In the *Simulators* menu select *Run* to start the simulation. Despending on simulator and complexity, a simulation takes between seconds and some minutes on a modern PC.

3. After the simulation has been performed, the LINEVIEW tool to display simualtion results will be started automatically. A graphical display is available for the following simulation results:

- Effective permittivity of a mode versus frequency
- Transported power of a mode versus frequency
- Dielectric and metallic losses of a mode versus frequency
- Current and voltage vectors of a mode versus frequency
- Per-unit-length matrices R', L', G', C' versus frequency
- n-port parameters for a strip section with a given finite length versus frequency
- SPICE equivalent circuit for a strip section with a given finite length
- Time domain behaviour for a strip section with a given finite length

LINMIC Interconnect allows the designers of strip sections to calculate the electrical behaviour from the geometry. Furthermore, substrate configurations can be determined so that an optimum match between measurement and simulation can be reached.