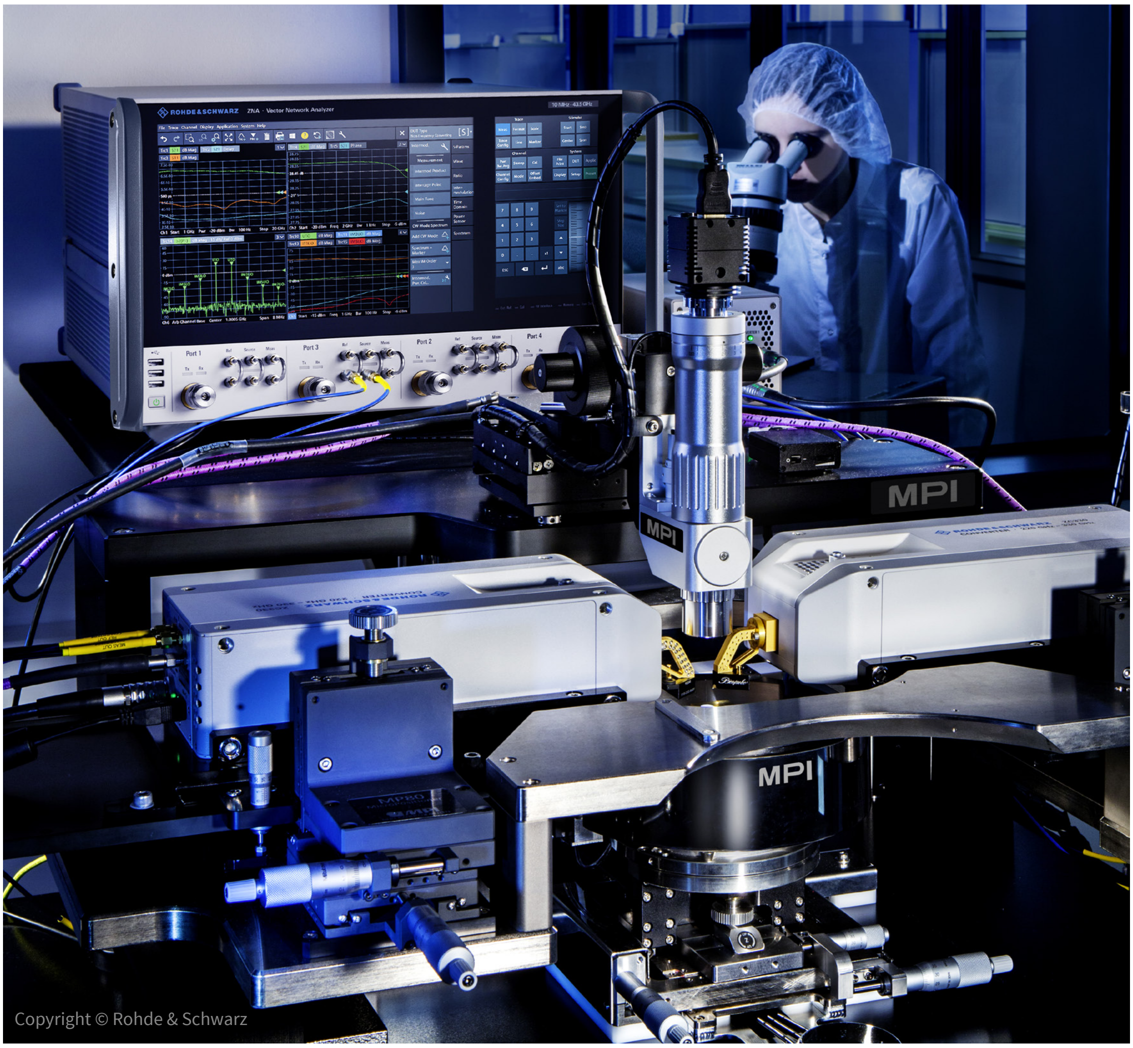
Simplifying the Art of Terahertz Measurements

Achieving metrology-level accuracy with a manual probe system

With significant expansion of emerging THz applications, such as non-invasive spectroscopy, security and surveillance, short range automotive radar and high-speed 5G communication, the need for accurate, reliable and repeatable measurement data has become more crucial than ever. This is especially true for the research and technology development of the devices, integrated circuits and new product building blocks serving the need of THz applications.

This application note discusses unique solutions developed by MPI Corporation to address challenges of wafer-level calibration and measurements at THz frequencies. The solutions for integration of the measurement instrumentation, frequent system reconfiguration, impact of an operator on the accuracy and repeatability of calibration, as well as the need for metrology-level analysis of the measured data are described in the following sections.



Integration of Test Instrumentation

Measurements at sub-THz frequencies usually require repeated and tedious system reconfiguration to switch between frequency bands. For example, the probe system and the vector network analyzer (VNA) have to be reconfigured and recalibrated six times to reach 750 GHz (Fig. 1). Acquiring cross-banded data of a device under test (DUT) is becoming an extremely time consuming exercise.

The conventional approach of mounting the sub-THz vector network analyzer (VNA) frequency extenders on the probe system requires elevation of the chuck and microscope and therefore reduces the system's mechanical stability. At the same time, increase in measurement frequency demands extremely accurate positioning of the RF probes on the DUT contact pads and calibration standards. As a result, accuracy and repeatability of system calibration decrease with frequency exponentially and characterization of the DUT becomes a very challenging task.

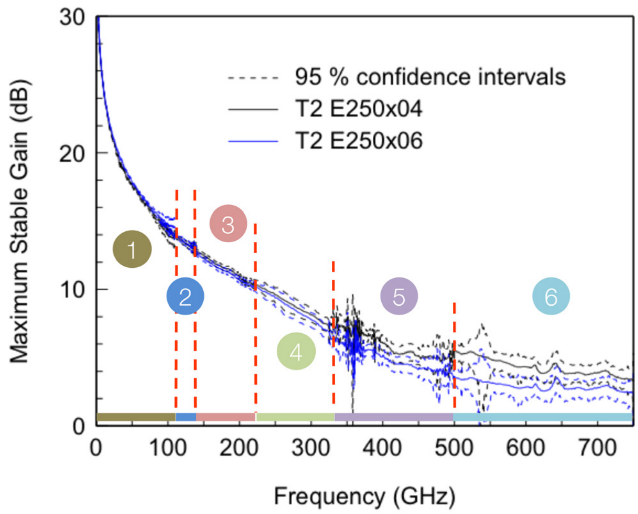


Fig. 1: Measurement up to 750 GHz requires six reconfigurations of the system. This example shows MSG measurements of THz transistors with 95% confidence interval.
Measured data are courtesy of Dylan Williams, NIST.

The manual TS150-THZ system was designed by MPI engineers from the ground up and incorporates many unique and innovative features. These include seamless integration of any type of ZNA frequency extenders at any frequency band to provide maximum possible measurement dynamic range and reproducibility of measurement results (Fig. 2). This common trade off was resolved by combining the low profile and stable chuck Z-stage with the ridged probe platen rested below its surface. This allows direct mounting of THz RF wafer probes on the output waveguide port of the ZNA frequency extenders and thus maximizes measurement dynamic range (Fig. 3).

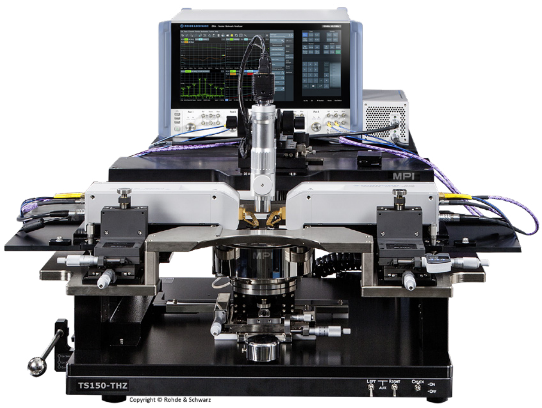


Fig. 2: The MPI TS150-THZ integrated probe system configured for measurement up to 330 GHz frequencies with the Rohde & Schwarz ZNA vector network analyzer. Picture is courtesy of Rohde and Schwarz.

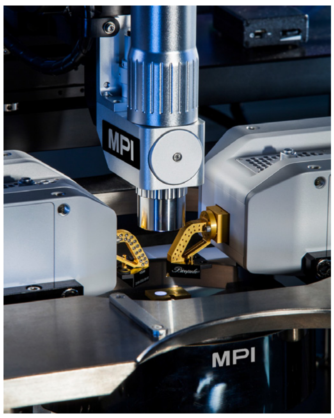


Fig. 3: The waveguide probes directly mounted at the output of the mm-wave ZNA converters. Picture is courtesy of Rohde & Schwarz.

A dedicated dove-tail interface of the ZNA extenders holding plates makes swapping them as easier than ever (Fig. 4). There is no need to unmount the interface plate from the extender. Due to its flat bottom, the interface and the ZNA extender can be easily located on the laboratory shelf or in a cabinet as one unit for further use.

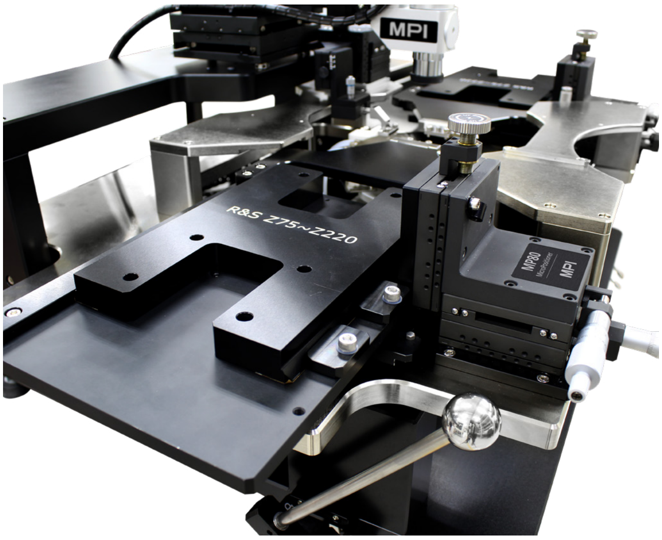


Fig. 4: The dove-tail interface of R&S®ZC75 to R&S®ZC220 frequency converters of the Rohde & Schwarz ZNA.

Why Multiline TRL?

The multiline Thru-Reflect-Line (TRL) RF calibration method developed at the U.S. National Institute of Standards and Technology (NIST) has quickly become the benchmark for metrology and industry laboratories focused on wafer-level RF measurement. Its key advantage over any other calibration method is the calculation of the calibration reference impedance Z_{REF} based on measurement of the traveling waves propagating through the calibration planar line standard. Traveling waves are purely physical phenomena defined by the type and design of transmission lines and are independent of the geometry and design of the RF probes. Additionally, the multiline TRL algorithm enables accurate extraction of the propagation constant γ of calibration lines. Therefore, the multiline TRL can set the measurement reference plane precisely and at an arbitrary position.

The multiline TRL calibration kit can be easily designed and fabricated using the same semiconductor process as the DUT. Customized „on-wafer" multiline TRL calibration kits eliminate the need for de-embedding the DUT measurement results from parasitic impedances of the device contact pads. Summarizing all these advantages, the multiline TRL is the only method that delivers trustable calibration results at measurement frequencies above 110 GHz.

Performing Multiline TRL with an MP80-DX MicroPositioner

Typically, three or more lines of different physical lengths should be used in the calibration to cover a wide frequency range. Together with the thru and reflect standards, the multiline calibration kit can include more than five elements. Measuring such a kit involves repeated re-adjustment of the MicroPositioners and re-alignment of the probes to the contact pads to achieve repeatable measurements. It is often difficult to obtain accurate and repeatable multiline TRL calibration at mm-wave frequencies on a manual probe system and especially if it is operated by several users having various levels of expertise.

The TS150-THZ system offers the pioneering option of the MP80-DX positioner: the integrated digital micrometer that enables outstanding simplicity for the multiline TRL. The TRL algorithm always treats the thru standard as a zero-length line. The length of each next line standards Δl is, therefore, defined with the respect to the length of the thru (Fig. 5). When operating the MP80-DX, the operator simply needs to zero-out the digital micrometer after the initial adjustment of the probes, i.e., on the thru standard (Fig. 6). Next, the distance between RF probes can be easily re-adjusted to the required value of Δl (Table 1) with the precision better than 1 μm. As a result, MP80-DX has boosted the accuracy and repeatability of the multiline TRL system calibration even for inexperienced operators while reducing set up times.

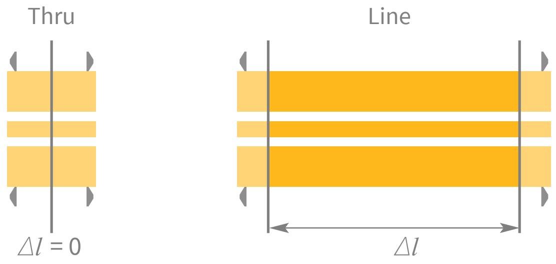


Fig. 5: The TRL definition of the Δl for line standards.

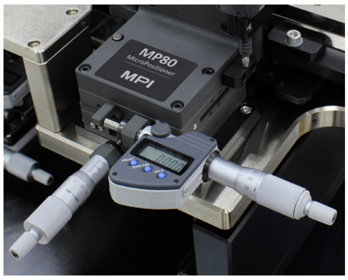


Fig. 6: The MP80-DX MicroPositioner with the digital micrometer on the X axes.

Table 1: Coplanar waveguide lines available from the commercial CS15 alumina calibration substrate

Standard type, (Name)	Physical length, µm	Effective length l, µm	Δl, µm
Thru	175	150	0
Line 1 (L2)	250	225	75
Line 2 (L3)	355	330	180
Line 3 (L4)	575	550	400
Line 4 (L5)	1025	1000	850
Line 5 (#10)	6600	6575	6425

StatistiCAL Plus and NIST Uncertainty Framework

StatistiCAL Plus is a software package developed at NIST that realizes both the conventional multiline TRL and calibration solutions based on the orthogonal distance regression. The algorithms were developed at NIST and the Physikalisch-Technische Bundesanstalt (PTB) of Germany. The unique feature of this algorithm is the ability to estimate the uncertainty of its own results due to random errors. The StatistiCAL Plus algorithm features a high degree of robustness as it is able to find solutions even with poor initial estimates.

The NIST Microwave Uncertainty Framework extends StatistiCAL Plus, enabling various data post-processing tasks related with calculating and propagating uncertainties through different models. The framework also includes post processors that allow the uncertainties in measured scattering parameters to be propagated to transistor gain, power, material parameters and other derived measurements and metrics.

Both software packages were developed for metrologists and microwave measurement experts with the intention of post-processing of already measured data in the “off-line” mode, *i.e.* without the link to the ZNA, probe system and device characterization software. Thus, their application in a typical industry or university measurement laboratory and the integration into a common automated measurement workflow is associated with enormous programming efforts and requires extensive experience in microwave metrology.

QAlibria® Integration with StatistiCAL Plus

For the first time, the NIST multiline TRL metrology-level ZNA calibration from StatistiCAL Plus can be easily accessed, thanks to its integration with QAlibria® - the calibration software from MPI. Both software packages work hand-in-hand in the system calibration and data analysis workflow (Fig. 7): QAlibria® takes responsibility for interaction with the ZNA, probe system and operator, while StatistiCAL Plus calculates calibration error terms and uncertainties running in the background. With the intuitive, multi-touch and multi-language graphical user interface of QAlibria®, configuration mistakes are minimized and accurate calibration results can be obtained quickly even by inexperienced users.

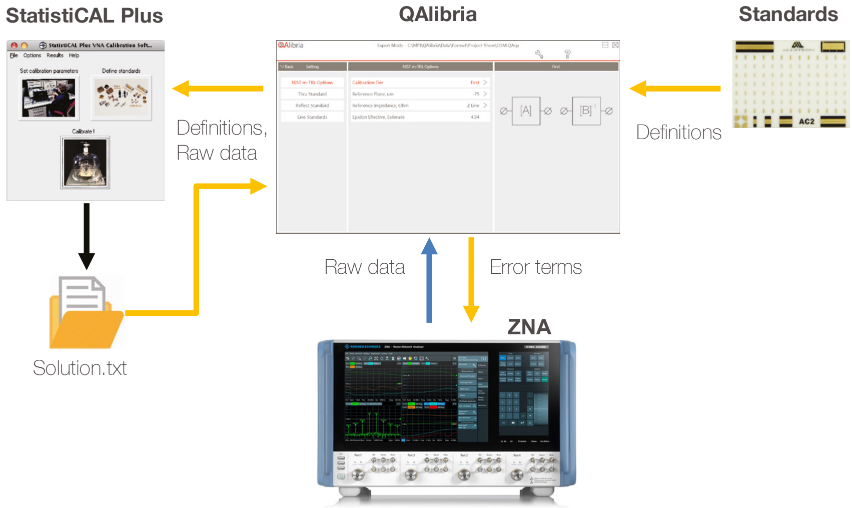


Fig. 7: System calibration data flow.

Calculating the multiline TRL error terms requires initial information about calibration standards, such as the type of the reflect standard (close to open or short), physical length of line standards, and initial estimate of the effective dielectric constant. In addition, the StatistiCAL algorithm requests the initial estimate for error terms and as well as some specific settings for the NIST ODRPACK calculation engine. All these definitions are automatically prepared by QAlibria® and saved locally as the StatistiCAL Plus calibration menu file "QAlibriaMenuNIST.scm" in the local folder "\MPI\QAlibria\Data\StatistiCAL\". This folder also contains raw data of calibration standards measured by QAlibria® (in the "_input\" directory) and the calibration results calculated by StatistiCAL and saved automatically as the solution vector "Solution.txt" in the "_output\" directory. Once StatisciCAL Plus calculations are completed, QAlibria® loads the solution vector and send the error terms to the ZNA. Therefore, the system is fully calibrated without any interaction from the operator side.

Calibration Repeatability and Reproducibility

TS150-THZ inherited common features of MPI manual systems, such as an air bearing stage, a highly repeatable platen lift with three discrete positions, and the auto-contact feature. The last is being especially important for improving contact repeatability and therefore improved reproducibility of DUT measured data independent of operator expertise.

Fig. 8 shows the experimental results for the calibration repeatability of the lumped line-reflect-match (LRM) and the multiline TRL methods performed on the TS150-THZ system and with the CS15 commercial alumina calibration substrates and waveguide RF probes from the same vendor. The LRM was executed twice sequentially and by the same experienced operator. The difference between these two calibrations was calculated using the calibration comparison method. Because the calibrations were performed sequentially, system drift was minimized and the outcome of the calibration comparison method primarily presents the repeatability error of the LRM calibration (Fig. 8, the red curve). Next, four multiline TRL calibrations were performed: two by an experienced operator and two by an inexperienced system operator. Each time the MP80-DX was used to define the Δl of each calibration line according to the Table 1. The difference in the maximum repeatability error of the multiline TRL calibration performed by two operators using the MP80-DX is significantly smaller than the single operator repeatability error of the LRM (Fig. 8, yellow curve).

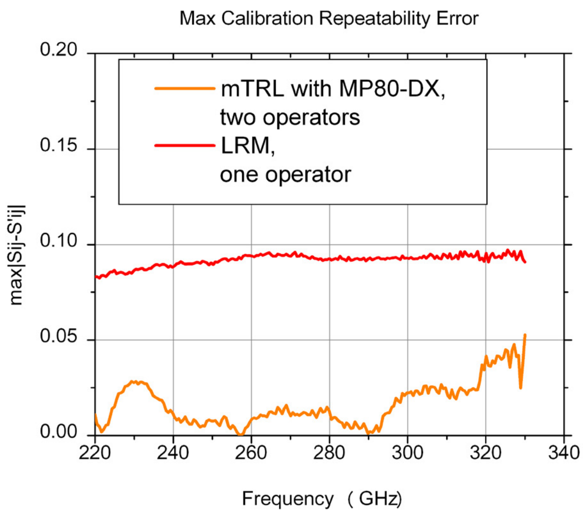


Fig. 8: Comparison of the repeatability of a lumped LRM calibration vs operator error for the multiple TRL calibration performed on the TS150-THZ with the MP80-DX option.

Examples of Calibration and Data Analysis

As was discussed above, the multiline TRL enables accurate extraction of the propagation constant γ of calibration lines. Therefore, the effective dielectric constant ε_{EFF} can easily be calculated. NIST StatistiCAL Plus can plot both the real and the imaginary parts of the ε_{EFF} for each line pair together with the average values (Fig. 9). This is a very handy feature for a quick verification and debug of calibration results. If required, the data can be exported as graphs or data files for further analysis processing.

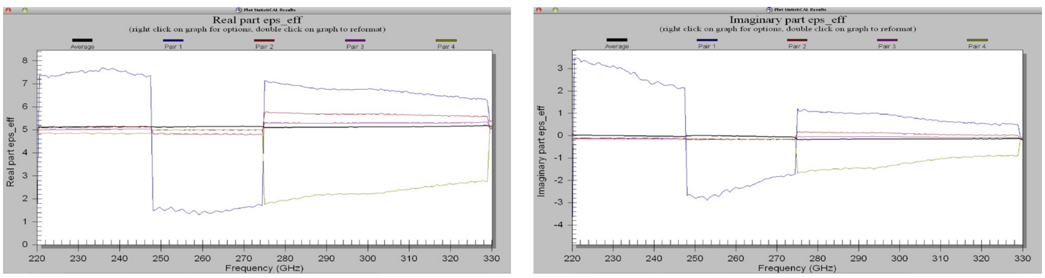


Fig. 9: The real (left) and the imaginary (right) parts of the effective dielectric constant ε_{EFF} calculated and displayed by the StatistiCAL Plus (debug case).

Another quick check of calibration success is to verify the corrected S-parameters of the line and reflect standards used for the calibration (Fig. 10, 11).

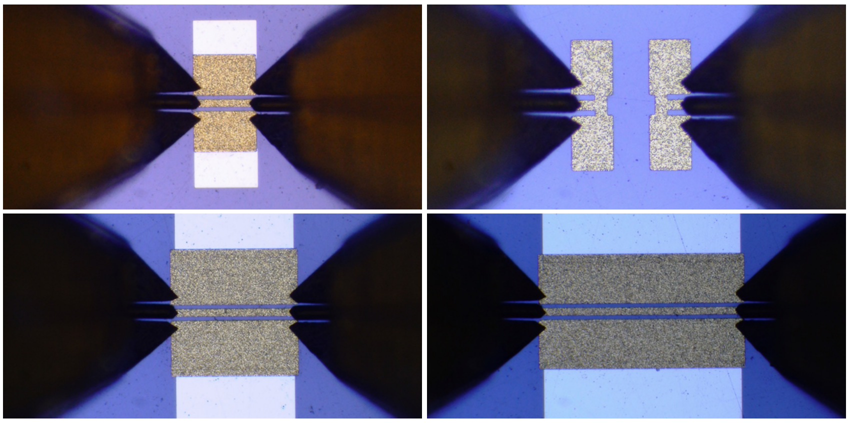


Fig. 10: Coplanar standards from the CS15 calibration substrate, from left to right: thru, short, line 2 and line 3.

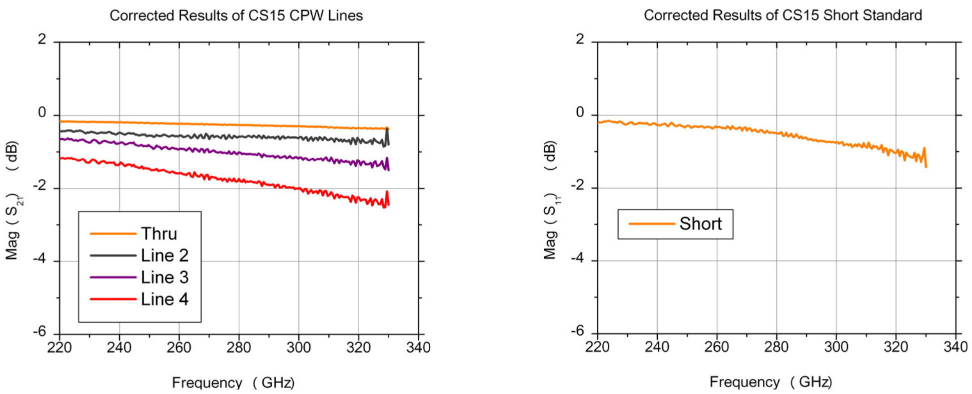


Fig. 11: The multiple TRL corrected results of the CPW lines and the short standards from CS15 calibration substrate.

When the detailed analysis of the DUT data including the calibration and measurement uncertainties is required, the StatistiCAL Plus solution vector can be directly loaded into the Calibrate DUT Plus tool from the NIST Uncertainty Framework and the DUT parameters can be calculated including the standard uncertainties with a 95% confidence interval. Additionally, the covariance matrix of calibration uncertainties should also be exported from the StatistiCAL Plus menu: Results\Save to File\Covariance Matrices (Fig. 12, 13).

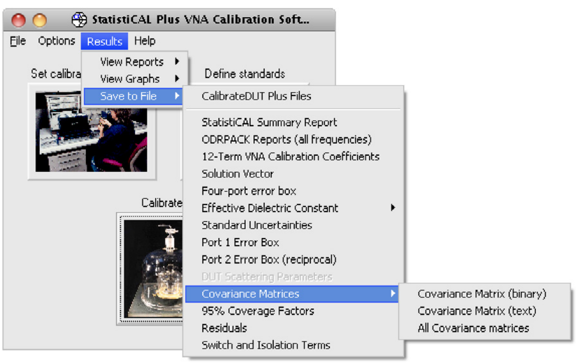


Fig. 12: Export of the calibration residual errors covariance matrix from StatistiCAL Plus

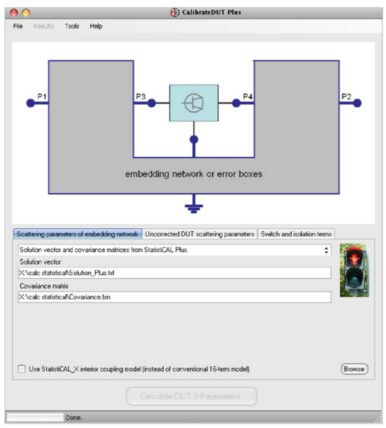


Fig. 13: The CalibrateDUT Plus tool from the NIST Uncertainty Framework package

To demonstrate system capabilities, a four-stage 325 GHz MMIC developed by the Fraunhofer Institute for Applied Solid State Physics IAF (Germany) was measured and the +/- 95% confidence interval was calculated for all results (Fig. 14). The Fig. 15 shows the results of its S21-parameter of the test LNA including the +/-95% confidence interval.

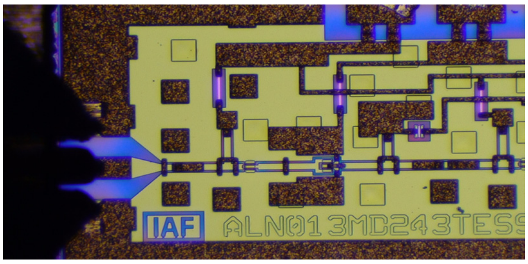


Fig. 14: The test four-stage 325 GHz MMIC. © Fraunhofer IAF

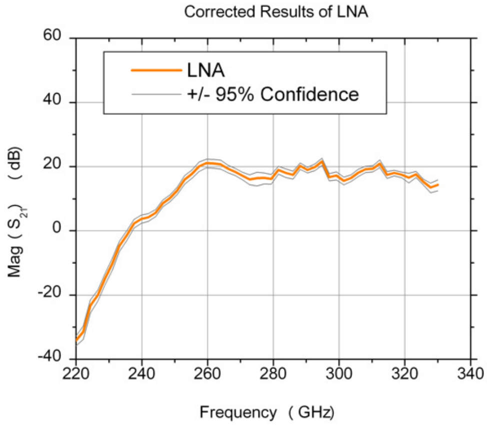


Fig. 15. The measured S21-parameter of the test MMIC measured with the respect to the multiline TRL including +/-95% confidence interval.

Conclusion

The expansion of the frequency band of the wafer-level measurement to the THz frequencies demands for new approaches for system integration, calibration, operation and data analysis. The TS150-THZ probe system incorporates decades of experience in RF measurement techniques from the management team of MPI's Advanced Semiconductor Test (AST) Division and leverages other AST products such as RF Probes, RF probing accessories and RF calibration software QAlibria®. The TS150-THZ was designed from scratch incorporating many unique and innovative features to simplify the system operation and re-configuration as well as to provide the maximum possible measurement dynamic range and reproducibility of measurement results. For the first time, it became possible to close the loop of the system calibration, device measurement and data analysis at the metrology level with outstanding simplicity due to unique integration of QAlibria® with NIST StatistiCAL Plus and the NIST Uncertainty Framework software packages.

With modular thermal and non-thermal chucks, MPI's advanced RF accessories such as, RF MicroPositioners, RF cables, calibration substrates and TITAN™ RF probes, new advanced calibration techniques combined with the integration of the ZNA closer to the DUT and the MPI partnership with Rohde & Schwarz, the TS150-THZ manual probe system becomes a complete measurement solution that addresses the complexities and accuracy requirements of THz probing.

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