Mastering the coaxial 1.0 mm connector interface

METAS has established SI traceability in 50 Ω coaxial S-parameter measurements up to 116.5 GHz. This work signifies the completion of a development that started about ten years ago and has led to major improvements of accuracy and consistency in coaxial S-parameter measurements. METAS provides now SI traceability for all major metrology-grade coaxial connectors, following the improved methodology that takes connector effects into account.

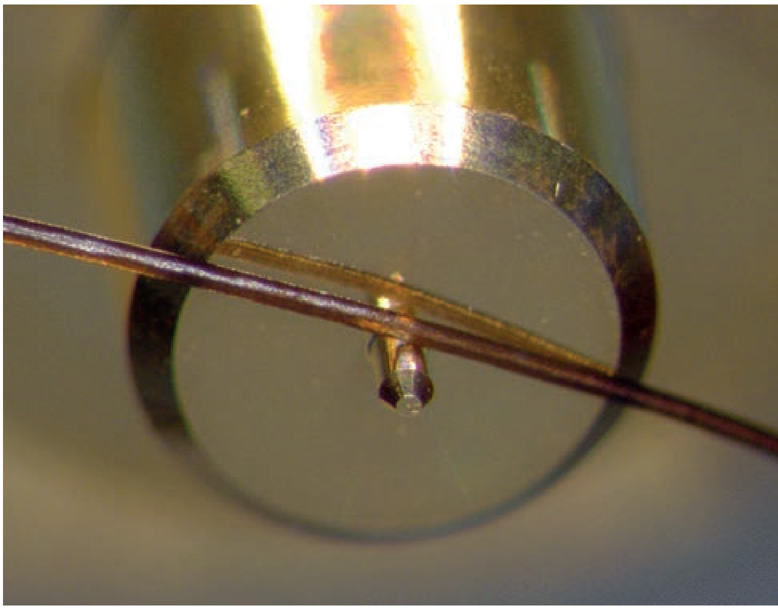
Markus Zeier

Communication technology is pushing towards higher frequencies in the electromagnetic spectrum to satisfy the hunger for more bandwidth. Technologies like wireless high-speed communication over short distance and automotive radar make use of frequency bands in the tenths of Gigahertz (GHz) and manufacturers of high-speed digital components show interest in test systems going beyond 100 GHz.

In all of these systems, electromagnetic signals need to be transmitted reliably and fast. Engineers and technicians rely on expensive measurement equipment to test the performance of components in that respect. To obtain conclusive measurement results, the measurement equipment needs to be calibrated properly. It is the role of metrology to provide the necessary reference standards, such that these measurements can be performed with the desired accuracy.

This article describes work at METAS which has been done to establish traceability to SI units for scattering parameters (S-parameters) in the 50 Ω coaxial line system up to 116.5 GHz. S-parameters are fundamental radiofrequency and microwave (RF & MW) quantities (see box), which play a crucial role in component design in the above mentioned technologies. Loosely speaking, they describe the response of the component under test with respect to an incoming high-frequent electromagnetic signal. An important property of S-parameters is that they can be cascaded easily, i.e. a system can be built up from individually characterized components, and the S-parameters of the whole system can be calculated through cascading. This modularity is very convenient for system design but it is also prone to amplification of small errors in the characterization of the individual components.

Coaxial transmission lines consist of a center and an outer conductor. Measurements in this system are limited to an upper frequency, which is determined by the diameters of the center and outer conductor. To suppress unwanted modes in electromagnetic propagation, the dimensions of the transmission line need to be smaller for higher frequencies. There are several standard diameters defined for different frequency bands. For measurements up to 116.5 GHz the standard coaxial line has diameters of 1.0 mm for the outer conductor and 0.434 mm for the center conductor. Connections in this line system rely on interconnects that have even smaller dimensions for the male pin and the female socket. Figure 1 shows a male pin in comparison with a human hair. Establishing SI traceability in the 1 mm line system means therefore (not exclusively but to a significant extent) to gain control over the delicate 1.0 mm connector interface.



1: 1.0 mm male flush short, consisting of a short plane and a male pin, in comparison with a human hair.

Methodology

S-parameters are measured with a vector network analyzer (VNA). The SI traceability of S-parameter measurements is established through calibration standards that are used to calibrate the VNA. These standards need to be calculable, i.e. a pure metallic structure is preferred and the geometry should be relatively simple. The standards are dimensionally characterized and the electrical properties are calculated as a function of frequency based on geometry and material properties. Traceability is established to the meter, the kilogram, the ampere and the second, four of the seven SI base units. Based on these primary standards, other VNA calibration standards, which do not need to be calculable, can be characterized.

In practice, the methodology to characterize primary standards is much more elaborate, as detailed in the sections below. The basics of the method have been developed 2006 to 2009 in a PhD thesis [1] in collaboration between METAS, ETH Zürich and industrial partners. It has led to a major improvement in the traceability of coaxial S-parameters in terms of accuracy and consistency. A major step forward was achieved when the connector interface was included in the characterization of the standards [2]. Previous work in S-parameter traceability always neglected the connector interface, which leads to inconsistencies among different VNA calibration algorithms. Another important ingredient is the VNA metrology software VNA Tools [3], which has been developed at METAS. Originally developed to be a software that calculates measurement uncertainties associated with S-parameters, it has been extended to support the SI traceable characterization of VNA calibration standards very efficiently. Finally, the calculations of the standards are supplemented by electrical measurements and it is crucial to have a stable measurement system and a well experienced operator who performs the delicate measurements with the necessary care.

Calculable calibration standards

The calculable 1.0 mm calibration standards are so-called offset shorts. They consist of a piece of line with air dielectric of varying length with a shorting plane attached to it and come with female and male connector interfaces. Figure 2 shows a schematic drawing of a male offset short indicating the three sections mentioned: connector interface, air-dielectric line section and short plane.

The standards used in this work have been specially developed in cooperation with Keysight Technologies (Keysight), one of the major manufacturers of VNAs and VNA calibration standards. For the design, METAS performed modelling of key features of the standards, as e.g. the lengths of the air-dielectric sections and mechanical aspects of the connector interfaces. Based on these suggestions, the standards were manufactured by Keysight, which has excellent machining and plating capabilities and the necessary experience to comply with the required tight tolerances.

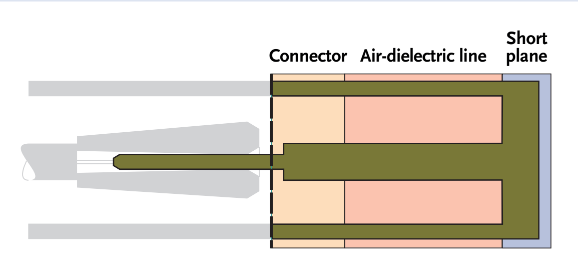
The standards were sent to METAS in a disassembled state. METAS performed the dimensional measurements on the individual components of the standards, thus having access to structures that would otherwise be difficult or even impossible to probe. An important role in these measurements played the METAS µCMM [4], a unique coordinate measuring machine, which is well suited to measure such small structures.

The measured components were then sent back to Keysight for assembly and returned to METAS again for further dimensional measurements, now in the assembled state. The standards were also subjected to first electrical measurements to test the electrical stability with repeated connections under varying angular orientations. Stability is a key property of any measurement standard. It directly limits the achievable accuracy. Only these repeatability measurements showed if a standard was suitable at all to be used in the further evaluations and in some cases replacements had to be fabricated.

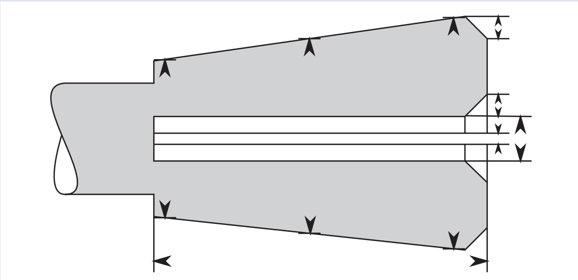
The mechanical measurement results are used later to calculate the electromagnetic properties of the standards as explained in the section on analysis and results. A mechanical model is therefore needed, which contains the key features of the standards impacting the electrical behavior. An example of such a model for the female connector interface is shown in figure 3. Similar models exist for the other sections in figure 2. The dimensions that are indicated with arrows in figure 3 need to be determined by measurements. A typical accuracy of a µm or better is desired. At 100 GHz, the wave length of the electromagnetic signal is 3 mm. A phase variation of 1 deg corresponds thus to a length of approximately 8 µm. This simple consideration illustrates the sensitivities with respect to the mechanical features.

Measurement setup

Commercially available VNAs usually cover frequencies up to 70 GHz. Beyond these frequencies, it is common practice to use in addition extender heads, which are connected via cables to a VNA. The extender heads multiply the signal from the VNA to the desired frequency. The reason for such an arrangement lies in the fact that at these high frequencies the signal cannot be transmitted over longer distances without significant loss. With the extender heads the high frequencies are generated close to the measurement plane and unnecessary loss can be avoided.



2: Model of a male offset short consisting of the three colored sections, connector, air-dielectric line and short plane. The greyed out part on the left side illustrates the mating female connector of the VNA test port. The black dashed line indicates the measurement plane.



3: Detailed model of the female connector interface. The dimensions indicated by arrows need to be measured.

4: Measurement setup for the 1.0 mm measurements with the two extender heads in the front (the two black boxes clamped between copper plates). Unique features of the setup are a free floating suspension system and a water cooling system for temperature control.

The METAS setup is shown in figure 4. It consists of a VNA from Keysight and WR10 extender heads from Virginia Diodes (VDI). The system has several unique features, which have been developed by METAS, to enhance the accuracy of the measurements.

One of the heads is kept fixed, whereas the other is suspended in a way that it is nearly free floating. This is achieved with additional weights to eliminate gravitational forces [5]. This way a nearly force-free connection of both heads can be achieved. This is important, because the connections are very sensitive to mechanical stress. A specially developed clamping system helps in addition to mechanically stabilize the measurement setup.

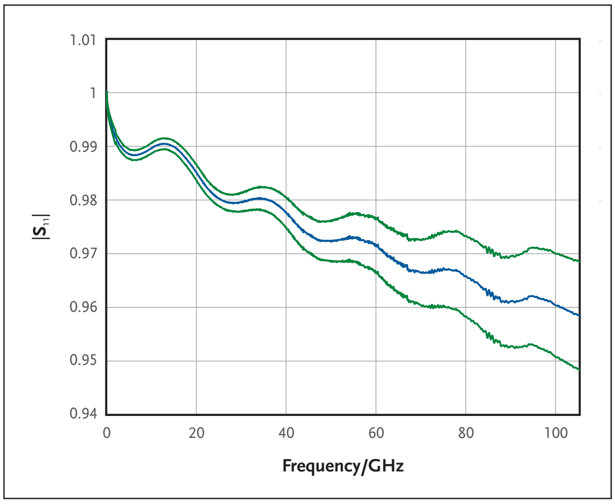
Without further measures the calibration standards would heat up during measurements, changing dimensions and electrical properties likewise. A water cooling system has therefore been installed [6] to keep the extender heads close to laboratory temperature. As an additional important benefit, the temperature control leads to a electrically much more stable measurement system. Before this improvement was implemented, the pressence of staff near the setup could lead to instabilities, something that largely vanished after installation of the temperature control.

Other improvements related to the VNA and the extenders were achieved by VDI and Keysight [7]. Altogether it took several iterations, by METAS and by the manufacturers, to finally obtain a measurement system that fulfilled the high stability requirements. Once this was achieved, the calibration standards were measured electrically.

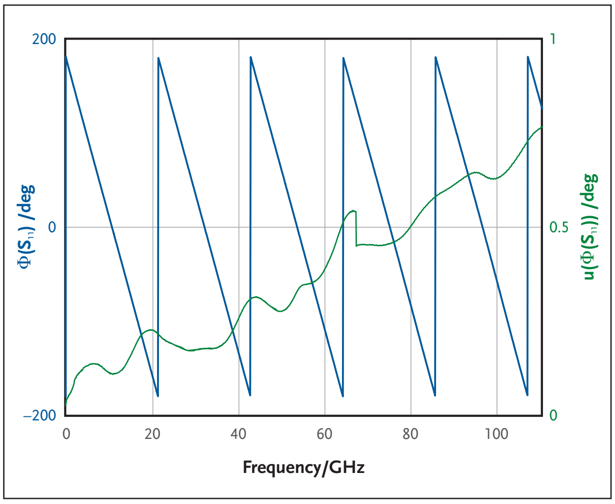
Analysis and results

The mechanical parametrization and the dimensional measurements of the calibration standards are used to calculate their electrical properties with a specially developed software tool. The software is capable to calculate the S-parameters of the whole standard, using a blend of analytical and numerical methods. It also propagates uncertainties in the dimensional characterization to uncertainties in the electrical properties.
This type of simulation is suitable to derive approximate S-parameters from the basic mechanical structures, but it is not so well suited to take material properties, as e.g. surface roughness and conductivity into account, simply because the information is often not available with the necessary accuracy. This is one of the reasons to use additional electrical measurements for the characterization of the standards.

By comparing the electrically measured raw S-parameters with the simulated S-parameters it is now possible to determine the remaining unknown parameters and thus the final calculated S-parameters of the calibration standards. Technically this is achieved through a nonlinear optimization technique. It is desirable to perform the optimization simultaneously over all frequency points, because some of the parameters are invariants with respect to frequency. This leads to a large optimization problem because several hundred frequency points are measured. In this particular problem 49 698 functions are minimized to determine 17 344 unknown parameters. This is not a trivial task but VNA Tools has built-in capability to perform this type of calculation [8, 9]. Using performance optimized software libraries the calculations can be executed on a state of the art PC with 64 GB RAM in 12 hours.



5: Magnitude of S_{11} of one of the 1.0 mm offset short standards in blue, bounded by the associated standard uncertainty interval in green.



6: Phase of S_{11} of one of the 1.0 mm offset short standards in blue, bounded by the associated standard uncertainty interval in green.

The differences between measured and calculated S-parameters, the so-called residuals, provide an excellent diagnostics tool to detect any problems and inconsistencies in the results. It is expected that the residuals are more or less evenly distributed and do not exceed a certain value. To understand the root cause of a problem is often not trivial. It can be as simple as a typographic mistake in one of the many input numbers, but in can also mean that one of the applied models is not adequately representing reality. Debugging can require a significant amount of persistence and scientific understanding and it is quite common that the optimization procedure needs to be repeated several times. Finally the desired consistency has been achieved and an example of the final S-parameters of one of the offset short standards can be seen in figures 5 and 6.

Conclusion

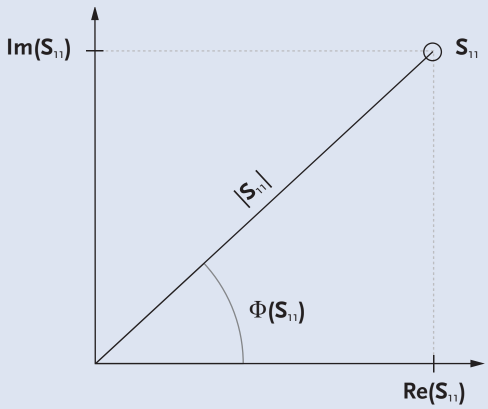
Establishing SI traceability for coaxial S-parameters in the 1.0 mm line system is not an easy task. It took METAS more than four years to overcome all obstacles and finally achieve the desired accuracy. As previously mentioned, the capability to

S-parameters

S-parameters are used to characterize reflection and transmission of a device upon impact of a high frequency electromagnetic signal. The figure below schematically represents the situation for a two-port device (e.g. an attenuation device) with input signals applied to both ports. If the device is linear, the output signals can be defined in terms of the input signals. Thus,

$$\mathbf{b}_1 = \mathbf{S}_{11}\,\mathbf{a}_1 + \mathbf{S}_{12}\,\mathbf{a}_2 \qquad \mathbf{b}_2 = \mathbf{S}_{21}\,\mathbf{a}_1 + \mathbf{S}_{22}\,\mathbf{a}_2$$

with the signal amplitudes $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{b}_1$ and $\mathbf{b}_2$ and the scattering parameters $\mathbf{S}_{ij}$. The scheme can be generalized to n ports and the equations can be written more economically in matrix form $\mathbf{b} = \mathbf{S}\mathbf{a}$ with the S-parameters contained in the scattering matrix $\mathbf{S}$ and the column vectors $\mathbf{a}$ and $\mathbf{b}$ containing input and output signal amplitudes, respectively. S-parameters are two-dimensional quantities either described in polar coordinates with magnitude $|\mathbf{S}_{ij}|$ and phase $\Phi(\mathbf{S}_{ij})$ or as complex numbers with real $\mathrm{Re}(\mathbf{S}_{ij})$ and imaginary $\mathrm{Im}(\mathbf{S}_{ij})$ parts.



cascade S-parameters is an important feature of S-parameters. By comparing measured and numerically cascaded S-parameters, it can be demonstrated that the new definitions of the calibration standards, taking the effects of the connector interface into account, lead to more accurate and consistent results [9].

The national metrology institutes (NMIs) declare their measurement capabilities in the key comparison database at the BIPM (www.bipm.org). A CMC (Calibration and Measurement Capabilities) entry in that database grants international recognition of certificates for the particular measurement service. METAS will be the first institute to have a CMC entry for coaxial S-parameter measurement up to 116.5 GHz. This entry completes the portfolio of METAS, now covering all major metrology grade coaxial line systems with the new methodology.

The newly established capability has already been used to provide SI traceability to a non-standard coaxial connector through an adapter de-embedding technique [10]. The MMPX connector is a proprietary connector developed by the Swiss company Huber+Suhner. Previously rated up to 67 GHz it can now be advertised for use up to 85 GHz, thus covering frequencies of interest for high speed digital testing, the next generation of mobile communication (5G) and the automotive sector. Being able to provide SI traceability in that connector system constitutes an advantage in these competitive markets.

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Die Beherrschung der koaxialen 1.0 mm Stecker-Schnittstelle

Die nach grösseren Datenraten strebende moderne Kommunikationstechnologie benötigt messtechnische Unterstützung bei immer höheren Frequenzen. Die zuverlässige Messung der Streuparameter ist für das Design solcher Systeme von grundlegender Bedeutung. Das METAS hat in einem Projekt mit Industriepartnern die Rückverfolgbarkeit auf SI-Einheiten für koaxiale Streuparameter bis 116.5 GHz realisiert. Dabei wurde ein spezieller Satz von Kalibrierstandards entwickelt und mechanisch und elektrisch vermessen. Die Stabilität des elektrischen Messsystems wurde durch thermische und mechanische Massnahmen deutlich verbessert. Die gewonnenen Messdaten wurden schlussendlich unter Verwendung analytischer und numerischer Rechenmethoden an Modelle angeglichen. Unter erheblichem Rechenaufwand konnte somit eine hohe Genauigkeit der Charakterisierung erreicht werden.

Diese Arbeit bedeutet den Abschluss einer Entwicklung, die vor etwa zehn Jahren begonnen hat, und zu wesentlichen Verbesserungen der Genauigkeit und Konsistenz bei der Messung koaxialer Streuparameter geführt hat. Ein wesentlicher Aspekt ist dabei die Berücksichtigung der Einflüsse der koaxialen Verbinder. Das METAS hat eine neue Methodik der Charakterisierung entwickelt und bietet jetzt entsprechende Kalibrierdienstleistungen für alle wichtigen Koaxialverbinder der Metrologie-Klasse an.

Maîtriser l'interface de connecteur coaxial de 1.0 mm

Les technologies modernes de la communication, qui tendent vers un débit de données plus important, nécessitent une assistance métrologique pour des fréquences toujours plus élevées. Une mesure fiable des paramètres S est primordiale pour la conception de tels systèmes. Au cours d'un projet avec des partenaires industriels, METAS a réalisé la traçabilité aux unités SI pour des paramètres S coaxiaux jusqu'à 116.5 GHz. Un jeu spécifique d'étalons a été développé à cet effet et soumis à des mesures mécaniques et électriques. La stabilité du système de mesure électrique a été nettement améliorée par des interventions au niveau thermique et mécanique. Enfin, les données de mesure ont été ajoutées aux modélisations par des méthodes de calcul analytiques et numériques. Une extrême précision dans la caractérisation a donc pu être atteinte par un calcul complexe.

Ce travail représente l'aboutissement d'un développement qui a débuté il y a environ dix ans et qui a donné lieu à des améliorations significatives de l'exactitude et de la cohérence lors de la mesure de paramètres S coaxiaux. La prise en compte des influences des connecteurs coaxiaux constitue un aspect essentiel de ce travail. METAS a développé une nouvelle méthodologie de caractérisation et propose à présent des prestations d'étalonnage correspondantes pour tous les connecteurs coaxiaux importants de classe métrologique.

Padroneggiare l'interfaccia connettore coassiale 1.0 mm

La moderna tecnologia della comunicazione, che mira a raggiungere velocità di trasmissione dei dati sempre maggiori, necessita di un supporto metrologico a frequenze sempre più elevate. Per progettare tali sistemi, è di fondamentale importanza poter misurare i parametri di dispersione in maniera affidabile. In un progetto portato avanti con partner industriali il METAS ha realizzato la riferibilità alle unità SI per i parametri di dispersione coassiali S fino a 116.5 GHz. È stato sviluppato un insieme specifico di standard di taratura, che è stato misurato meccaniche ed elettriche. La stabilità del sistema elettrico di misurazione è stata significativamente migliorata mediante provvedimenti termici e meccanici. Infine i dati di misurazione ottenuti sono stati equiparati a modelli utilizzando metodi di calcolo analitici e numerici. Con un notevole sforzo computazionale è stato quindi possibile conseguire un'elevata precisione della caratterizzazione.

Questo lavoro segna il completamento di uno sviluppo iniziato circa dieci anni fa, che ha condotto a miglioramenti significativi della precisione e della coerenza nella misurazione dei parametri di dispersione coassiali. Un aspetto importante di tale approccio è quello di considerare l'influenza dei connettori coassiali. Il METAS ha sviluppato una nuova metodologia per la caratterizzazione e fornisce ora adeguati servizi di taratura per tutti i principali connettori coassiali della classe metrologica.