DOI 10.5162/Ultrasonic2025/C2-a3

S-Parameter based Ultrasonic Transducer Characterization: a case study for high-frequency SAM-Transducers

Emanuel Leipner[1], *Mario Wolf*[1], *Stefan König*[3], *Peter Hoffrogge*[3], *Peter Czurratis*[3], *and Christian Kupsch*[1,2]
[1] *TU Bergakademie Freiberg, Measurement, Sensor and Embedded Systems Lab (MSE Lab), Freiberg, Saxony, Germany*
[2] *TU Bergakademie Freiberg, Center for Efficient High Temperature Processes and Materials Conversion (SN0390002), Freiberg, Saxony, Germany*
[3] *PVA TePla Analytical Systems GmbH, Westhausen, Baden-Württemberg, Germany*
emanuel.leipner@mse.tu-freiberg.de

Abstract: We present a case study applying an S-parameter-based method for characterizing SAM transducers from 20 MHz to 1 GHz. Leveraging the bandwidth and calibration accuracy of vector network analyzers, this approach enables consistent extraction of both electrical impedance and acoustic response. The results demonstrate the method's value in isolating transducer behavior, supporting system-level integration, and facilitating repeatable, high-frequency performance evaluation in scanning acoustic microscopy.

Keywords: Transducer Characterization, transient transducer characterization, Scattering Parameters, time-frequency-analysis, Scanning Acoustic Microscopy (SAM)

Introduction

Scanning Acoustic Microscopy (SAM) is an essential tool in chip manufacturing, providing non-destructive inspection capabilities crucial for quality control and defect detection. The performance of SAM systems heavily relies on the optimization of ultrasonic transducers tailored to specific applications. These transducers operate at high frequencies and employ highly focused ultrasound, covering a wide range of bandwidths from 20 MHz to 1 GHz.

The characterization of SAM transducers is challenging due to the complex interactions between the transducers and the transceiver system. Traditional characterization methods yield system responses that are a convolution of the transceiver and transducer responses, making it difficult to isolate and optimize transducer performance. This issue is exacerbated by the need for different transceivers for various frequency ranges and the coupling of acoustic and electrical domains [1].

To address these challenges, we present a case study demonstrating the application of an S-parameter based characterization method to high-frequency SAM transducers. This method separates the acoustic and electrical domains, providing pure transducer characteristics and enabling optimal system integration and performance enhancement. The case study includes the characterization of transducers with two focusing mechanisms, covering frequencies up to 1 GHz.

By showcasing this method in the field of high-frequency SAM transducer development, we aim to demonstrate its applicability across a wide range of configurations and excitation schemes. Furthermore, this work establishes the S-parameter-based approach as a general and powerful tool for transducer characterization. It allows for precise performance assessment and facilitates the systematic optimization of transducers for integration into advanced SAM systems.

S-Parameter Based Characterization Method

The S-parameter based characterization method offers a novel approach to isolating and optimizing the performance of ultrasonic transducers used in scanning acoustic microscopy (SAM). This method leverages the principles of radio frequency (RF) engineering and the capabilities of Vector Network Analyzers (VNAs) to separate the acoustic and electrical domains, providing pure transducer characteristics. The process involves measuring the S-parameters in the frequency domain, which represent the ratio of the reflected wave to the incident wave at a specific port. By performing calibrations with known standards, the VNA can eliminate the effects of the measurement system, including cables and connectors, and isolate the response of the ultrasonic transducer. The frequency-domain data is then transformed into the time domain using the inverse Fourier transform, allowing for the application of time-domain gating to separate the acoustic and electrical signals. This approach enables the extraction of both the electrical properties and the acoustic signal of the transducer, providing a comprehensive understanding of its behavior.

Principles of S-Parameter Measurements

Scattering parameters (S-parameters) are used to describe the electrical behavior of electrical n-port networks in radio frequency (RF) engineering. For increased frequency, the typical assumption of concentrated elements in electrical circtuit analyses does not hold and voltages and currents are functions of time and space. Additionally, electrical energy exhibits wave-like propagation behavior, and effects such as reflection at interfaces where impedances change become relevant. A measured voltage at a given moment in time and at a defined point in space would still include the superposition of incident and reflected waves.

To deal with this effect, S-parameters are defined as the ratio of the reflected wave to the incident wave at a specific port - a conceptual interface in an RF network where power flow, voltage, and current are defined and measurable. For an n-port network, the elements $\underline{s}_{ij}$ of the S-parameter matrix $\underline{S}$ (where the underline denotes complex-valued quantities) are given by:

$$\underline{s}_{ij} = \left.\frac{b_j}{a_i}\right|_{a_k=0 \text{ for } k\neq i} \tag{1}$$

where a_i represents the incident wave at port i, b_j represents the reflected wave at port j, and the condition $a_k = 0$ for $k \neq i$ indicates that all other ports are terminated with matched loads.

In the case of ultrasonic transducers, which are typically modeled as 1-port networks, the primary S-parameter of interest is $\underline{s}_{11}$, representing the reflection coefficient at the port. Measuring $\underline{s}_{11}$ over a frequency range provides insights into both the electrical impedance and the acoustic behavior of the transducer.

S-Parameter Measurement - VNA and Calibration

The measurement device used in this method is a Vector Network Analyzer (VNA). To perform the measurement, we must define the reference plane, which is done by calibrating the VNA with known standards. This is done with an 16-term error correction approach measuring the standards Thru, Open, Match, Short (TOMS) and using these measurements to correct for any systematic errors in the measurement system, including the effects of cables and connectors [2].

The calibration process ensures that the measured S-parameters accurately represent the isolated transducer response, including both the electrical and acoustical domains. The result is a set of S-parameters that describe the transducer's behavior over the desired frequency range.

Separation of the Electric and the Acoustic Domains by Time-Domain Gating

To separate the acoustic and electrical domains, time-domain gating [3] is employed. It involves applying a window function to the time-domain impulse response to isolate the electrical signals from the acoustic reflections. Since electrical waves travel at the speed of light and acoustic waves at the much slower speed of sound, their time of flight differs. As a result, the early part of the signal reflects the electrical properties of the transducer, while later components reveal acoustic effects.

The frequency-domain data is transformed into the time-domain using the discrete inverse Fourier transform (iDFT):

$$\underline{x}_{11}(k) = iDFT\left(\underline{s}_{11}(f)\right) \tag{2}$$

where $\underline{s}_{11}(f)$ is the frequency-domain reflection coefficient, and $\underline{x}_{11}(k)$ is the time-domain impulse response.

The gated time-domain response can be expressed as:

$$x_{11,\text{gated}}(k) = x_{11}(k) \cdot w(k) \tag{3}$$

where $w(k)$ is the window function. This window $w(k)$ includes only time samples prior to the arrival of the first acoustic signal component, $k\Delta t < t_{\text{acoustic}}$ where Δt is the time resolution.

After transforming this subset $x_{11,\text{gated}}(k)$ back into the frequency domain by applying the DFT, the result can be used to compute the complex impedance $\underline{z}_{11}$ as follows [4, p. 181]:

$$\underline{s}_{11,\text{gated}}(f) = DFT\left(x_{11,\text{gated}}(k)\right) \tag{4}$$

$$\underline{z}_{11} = Z_0 \frac{1 + \underline{s}_{11}}{1 - \underline{s}_{11}(t)} \tag{5}$$

To extract the acoustic response and enhance the time resolution, the frequency-domain measurement $\underline{s}_{11}$ is extended to a symmetric vector. This involves synthetically adding the DC point and the complex-conjugated, mirrored copy of the measured N frequency points to create a symmetric spectrum. The iDFT is then calculated to obtain a real-valued time signal.

A time gate is applied to the time signal to extract the remaining part of the time signal $x_{11}(k)$ for

$k\Delta t > t_{\text{acoustic}}$, which corresponds to the acoustic response of the transducer. This process effectively separates the acoustic and electrical domains, providing a pure acoustic response.

Experimental Setup

The experimental setup for the S-parameter-based characterization method includes a ZNB4 vector network analyzer (Rohde & Schwarz GmbH & Co. KG, Munich, Germany), a ZN-Z135 calibration kit for TOMS-calibration, and a selection of high-frequency SAM transducers (PVA TePla Analytical Systems GmbH, Westhausen, Germany). The transducers under investigation employ two distinct focusing mechanisms: curved piezoelectric elements, where the element itself focuses the wave, and sapphire acoustic lenses, where a planar element generates the wave and a sapphire body shapes it to a focal spot (see Tab. 1).

Tab. 1: Overview of Transducer Specifications [5]

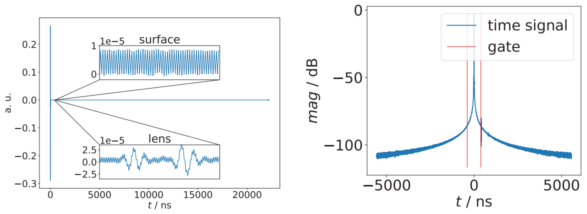
No.	Name	Focusing Mechanism	Focus Position
1	Transducer $30\,\text{MHz}$	curved element	$12.7\,\text{mm}$
2	Transducer $150\,\text{MHz}$	sapphire lens	$8\,\text{mm}$
3	Rayleigh wave lens $1.000\,\text{MHz}$	sapphire lens	$80\,\mu\text{m}$

The VNA was configured to perform S-parameter measurements in reflection mode. To avoid aliasing in time domain, it is essential to measure low frequency components as these components define the base period of the time signal. Further, to synthetically include the DC point, the lowest measured frequency also defines the frequency step size of the sweep. The maximal frequency must cover the expected frequency range of the transducer and corresponds to the inverse time resolution of the time-domain signal.

Results

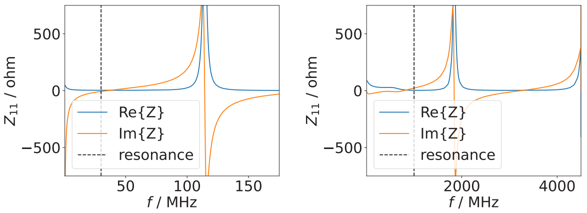
Raw Measurement Time Signals and Time Gating

To illustrate the effectiveness of the S-parameter-based characterization, we now present the time-domain signals obtained from the VNA measurements. These were calculated as has been explained in section . The examples highlight how time-domain gating enables separation of electrical and acoustic components for further evaluation. Fig. 1 shows a raw time-signal of the transducer no. 3 and its correspondent time-gate.

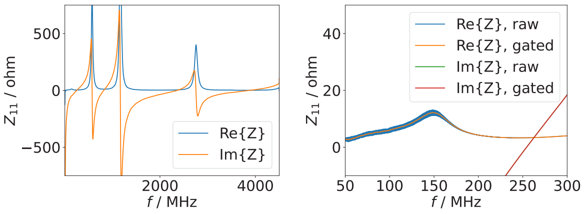


(a) raw time-signal *(b) time-domain gating*

Fig. 1: Raw magnitude of the S-parameter measurement $\underline{x}(k\Delta t)$ and the corresopndent time-signal and the time-gate applied for transducer no. 3.



(a) Transducer No. 1 *(b) Transducer No. 3*



(c) Transducer No. 2 *(d) Transducer No. 2, zoom*

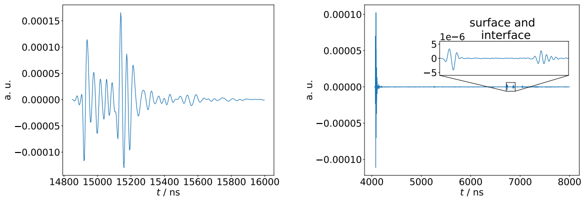
Fig. 2: Real and imaginary parts of the impedance $\underline{z}_{11}$ for three transducers. Subfigure (d) shows a zoomed view around the resonance of the $150\,\text{MHz}$ transducer, comparing raw and gated data.

It is clearly visible that small echo amplitudes are heavily affected by noise, indicating the need for further filtering. The initial portion of the signal contains the electrical reflection, followed by two distinct acoustic pulses corresponding to the interface between the sapphire lens and water. The surface echo is barely distinguishable from the noise floor. A band-pass filtered version of the acoustic signal is shown in Fig. 3c.

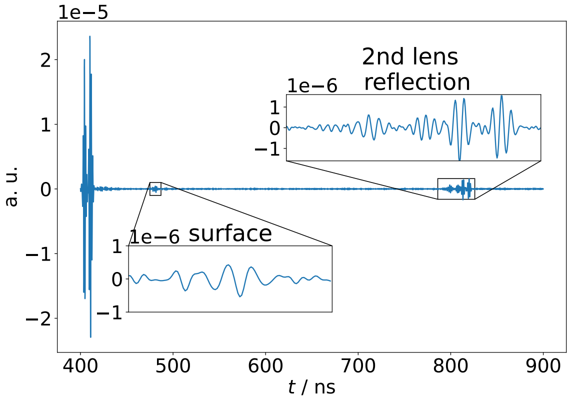
Impedance Curves

The frequency-dependent impedance of the ultrasonic transducers is extracted from the S-parameter data, as shown in Fig. 2. These impedance curves provide insight into the electrical behavior of the transducers, including resonance characteristics and coupling efficiency.

Time-domain gating reduces unwanted reflections and system-induced artifacts, resulting in a cleaner



(a) Transducer No. 1 *(b) Transducer No. 2*



(c) Transducer No. 3

Fig. 3: Bandpass filterd time signals $x_{11}(k\Delta t)$ for three different transducers.

impedance response that more accurately represents the intrinsic behavior of the transducer, as demonstrated in Fig. 2d.

Importantly, the electrical and acoustic resonance frequencies are not aligned, see Fig. 2d. This mismatch indicates an opportunity for optimization: aligning these resonances could improve energy transfer between the electrical and acoustic domains, thereby enhancing transducer efficiency and operational bandwidth.

A-Scan Signals

A-Scan signals are obtained by analyzing the time-domain responses of the transducers, see Fig. 3. These signals represent the amplitude of the reflected ultrasonic waves as a function of time, providing information about the internal structure and defects within the sample. To enhance signal quality, band-pass filtering is applied to reduce the noise floor.

These results demonstrate that a wide range of transducers can be characterized using a single, broadband measurement setup without the need for dedicated transceiver hardware. The method achieves a dynamic range of approximately 88 dB, enabling reliable identification of both strong and weak acoustic echoes. This includes reflections within the lens structure and from sample interfaces, confirming the method's suitability for high-resolution, quantitative A-scan analysis in scanning acoustic microscopy.

This highlights the versatility of the VNA-based method in capturing both weak and strong acoustic features with a single, broadband measurement.

Conclusion

We presented an S-parameter-based method for characterizing ultrasonic transducers in SAM systems. By separating electrical and acoustic domains using VNA measurements and time-domain gating, the method enables accurate impedance and A-scan analysis. It covers the typical 20 MHz to 1 GHz frequency range used in SAM applications, supporting efficient transducer evaluation and optimization with a single, broadband setup.

Acknowledgment

The research is funded by German Federal Ministry for Research, Technology and Space (BMFTR) under the reference number 13XP5187F, and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project number 427525397.

References

[1] E. Leipner, M. Wolf, and C. Kupsch. “Characterization of high-frequency ultrasonic transducers using S-parameters: Separation of electrical and acoustic responses”. In: *Mechanical Systems and Signal Processing* 238 (2025), p. 113172. ISSN: 0888-3270. DOI: https://doi.org/10.1016/j.ymssp.2025.113172. URL: https://www.sciencedirect.com/science/article/pii/S0888327025008738.

[2] H. Van Hamme and M. Vanden Bossche. “Flexible vector network analyzer calibration with accuracy bounds using an 8-term or a 16-term error correction model”. In: *IEEE Transactions on Microwave Theory and Techniques* 42.6 (1994), pp. 976–987. DOI: 10.1109/22.293566.

[3] Z. Chen and Z. Xiong. “Differences of Time Domain Gating Implementions in Vector Network Analyzers”. In: *2019 Joint International Symposium on Electromagnetic Compatibility, Sapporo and Asia-Pacific International Symposium on Electromagnetic Compatibility (EMC Sapporo/APEMC)*. 2019, pp. 597–600. DOI: 10.23919/EMCTokyo.2019.8893825.

[4] D. M. Pozar. *Microwave Engineering*. en. 4th ed. Chichester, England: John Wiley & Sons, Nov. 2011.

[5] P. T. A. S. GmbH. *Transducer / Range*. 2025. URL: https://www.pvatepla-sam.com/en/products/transducer/ (visited on 06/23/2025).