



HAL
open science

Comparison of Impedance Matching Networks for Scanning Microwave Microscopy

Johannes Hoffmann, Sophie de Préville, Bruno Eckmann, Hung-Ju Lin, Kamel Haddadi, Didier Théron, Georg Gramse, Damien Richert, José Morán-Meza, François Piquemal, et al.

► To cite this version:

Johannes Hoffmann, Sophie de Préville, Bruno Eckmann, Hung-Ju Lin, Kamel Haddadi, et al.. Comparison of Impedance Matching Networks for Scanning Microwave Microscopy. *IEEE Transactions on Instrumentation and Measurement*, 2024, 73, pp.6006109. 10.1109/TIM.2024.3378310. hal-04777082

HAL Id: hal-04777082

<https://hal.science/hal-04777082v1>

Submitted on 12 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL
open science

Comparison of Impedance Matching Networks for Scanning Microwave Microscopy

Johannes Hoffmann, Sophie de Préville, Bruno Eckmann, Hung-Ju Lin, Benedikt Herzog, Kamel Haddadi, Didier Théron, Georg Gramse, Damien Richert, José Morán-Meza, et al.

► **To cite this version:**

Johannes Hoffmann, Sophie de Préville, Bruno Eckmann, Hung-Ju Lin, Benedikt Herzog, et al.. Comparison of Impedance Matching Networks for Scanning Microwave Microscopy. *IEEE Transactions on Instrumentation and Measurement*, 2024, 73, pp.6006109. 10.1109/TIM.2024.3378310. hal-04777082

HAL Id: hal-04777082

<https://hal.science/hal-04777082v1>

Submitted on 12 Nov 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Comparison of Impedance Matching Networks for Scanning Microwave Microscopy

Johannes Hoffmann¹, Sophie de Preville¹, Bruno Eckmann¹, Hung-Ju Lin¹, Kamel Haddadi², Didier Theron²
Georg Gramse³, Damien Richert⁴ José Morán-Meza⁴ and Francois Piquemal⁴ Benedikt Herzog

¹Federal Institute of Metrology METAS Johannes.Hoffmann@metas.ch

²Institut d'Electronique, de Microelectronique et de Nanotechnologie, Universite Lille

³Johannes Kepler Universität (JKU)

⁴Laboratoire National de Métrologie et d'Essais (LNE)

Abstract—In this paper, a definition of the gain and added noise of impedance matching networks for scanning microwave microscopy is given. This definition can be used to compare different impedance matching techniques independently of the instrument used to measure the S-parameter. As a demonstration, impedance matching devices consisting of a Beatty line, a tuner, and interferometric setups with and without amplifiers have been investigated. Measurement frequencies up to 28 GHz are used, and the maximal resulting gain found was 9504.7 per Siemens.

Index Terms—Impedance, Impedance Matching, Scanning Microwave Microscopy, Gain Measurement, Noise Measurement

I. INTRODUCTION

In scanning microwave microscopy (SMM), a vector network analyzer (VNA) is connected through an impedance-matching network to a modified atomic force microscope (AFM) supporting a conductive tip. The VNA sends a signal through the matching network to the AFM tip. There, the signal is reflected back to the VNA as a function of the material properties or local impedance below the tip. Microwave hardware is usually built for 50 Ω characteristic impedance, but the impedances to be measured at the tip are in the range of k Ω . This impedance mismatch needs to be compensated for by a matching network to enable low noise and high signal measurements.

Various methods for creating such matching networks have been researched in the past. In [1] general techniques of measuring very high impedances with a VNA using different couplers are discussed, and comparisons of measurement noise with and without the matching network are made. In [2] and as well in [3], comparisons between no matching network, a network consisting of a shunt and a $\lambda/2$ line, and a 90 degree hybrid in combination with a low noise amplifier have been made. In the proceedings paper [4] the authors of the present paper described the measurement technique for a setup containing a Beatty line as an impedance matching network.

The studies about improving existing or new matching networks have in common that the results are not comparable between different studies because the noise coming from the VNA has not been taken into account. Here, matching networks consisting of a Beatty line, a tuner, and two interferometric setups have been investigated. A theoretical calculation of the expected gain is presented. A technique

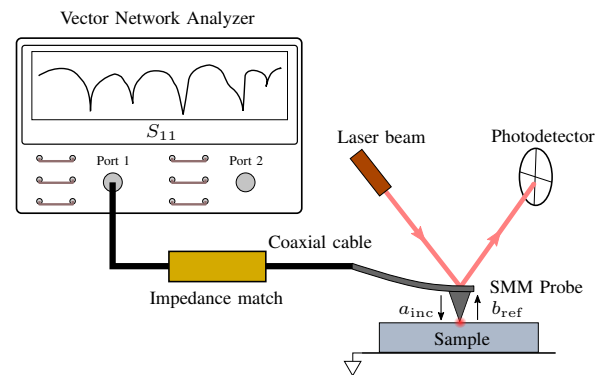


Fig. 1. Schematic of SMM setup at METAS and JKU. In the case of METAS the matching element between VNA and tip is a Beatty line, a 25 Ω mismatch section. In the case of JKU the matching element is a tuner.

to practically quantify the gain and added noise of a given matching network is introduced. These figures of merit enable comparison and application dependent selection of network topologies. Additionally, two different techniques to obtain the raw data are tested. One works with a retraction scan where different capacitance values are measured at different heights. The second is based on a calibration sample containing known capacitors.

The authors use the following impedance matching networks in their labs and test these setups with the aforementioned technique. The setup at METAS consists of a Rohde Schwarz ZNA 50 with a Beatty line connected to a Nanosurf FlexAFM with an SMM cantilever; see fig. 1. The Beatty line is in essence a piece of 25 Ω transmission line which produces reflections that, at certain frequencies, minimize the reflection coming from the tip. In terms of a matching network, this is most probably the approach requiring the fewest parts and thus the most stable over time.

The setup at JKU consists of a 50 GHz Keysight PNA L with frequency extension and a Keysight SMM. The impedance matching network consists of a Mauri 1643P tuner; see fig. 1. The tuner can improve the match at arbitrary frequencies. This setup does not contain active elements apart from the VNA and is expected to be stable over time.

The matching network at LNE is a home-built Mach-

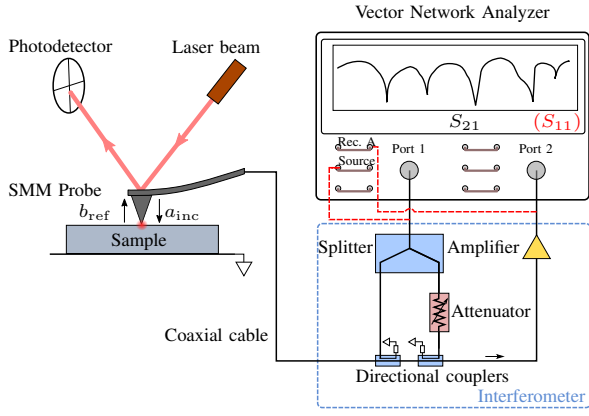


Fig. 2. Schematic of SMM setup at LNE and the University of Lille. In the case of LNE the interferometer is directly connected to the test ports whereas University of Lille uses direct receiver access.

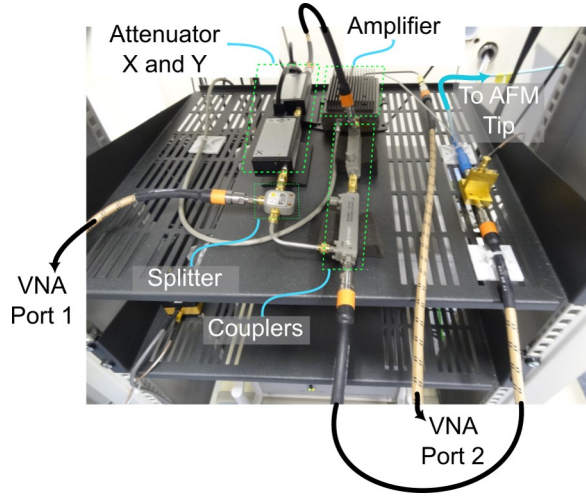


Fig. 3. Photograph of the Mach-Zehnder-based interferometric impedance matching system at LNE.

Zehnder-based interferometric system (see figs. 2 and 3) using microwave electronic devices purchased from Keysight Technologies. The interferometer was built using a coaxial divider (model 11636B: DC – 26.5 GHz, power divider), two coaxial directional couplers (model 87300C: 1 – 26.5 GHz), two programmable step attenuators (model 84904K: DC – 26.5 GHz, 22 dB attenuation total range, selected attenuation=7 dB and 21 dB), and a microwave system amplifier (model 83017A: 0 – 26.5 GHz, 25 dB minimum gain). The VNA is a P9374A.

The setup at the University of Lille is schematically the same as the one used at LNE but with direct receiver access; see fig. 4. The advantage of this configuration is that only one port of the VNA is occupied, and the SNR is better because coupling losses at the test port coupler are avoided. These coupling losses at the test port without direct receiver access are approximately 13 dB in VNA of the University of Lille.

II. THEORY AND TECHNIQUES

The objective of the techniques described is to extract the gain of the matching network and its added noise. In order to determine the gain, one measures with the SMM two different

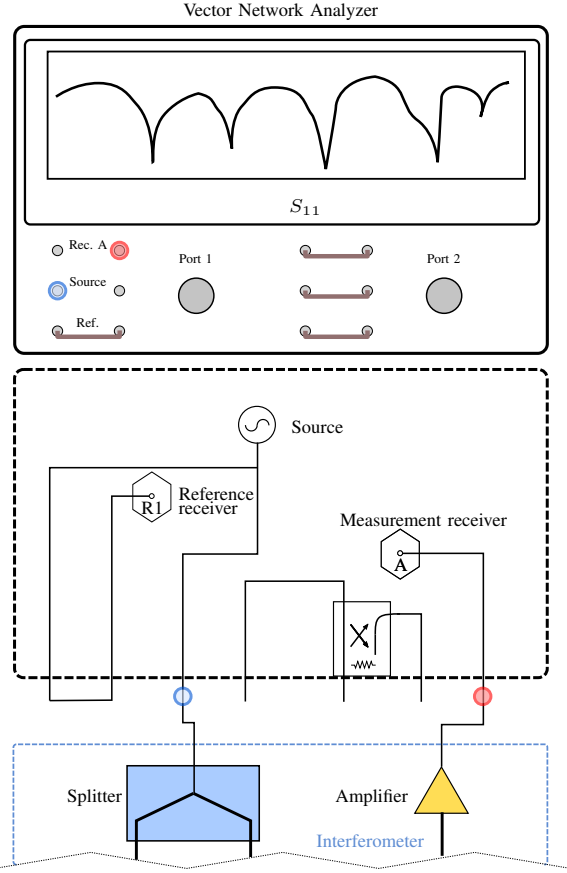


Fig. 4. Illustration of direct receiver access at port one. Instead of connecting the divider to the test port, it is directly connected to the source (red) and the amplifier is directly connected to the receiver (green) at port one. The blue arrow indicates the test port in schematic and photo of a VNA.

admittances. This can be done in a retraction scan or while scanning over a sample with known admittances. From this image or retraction scan, one can extract the raw reflection S_{11} or transmission S_{21} of two different known admittances at the tip. The gain of the matching network can now be computed as

$$G = \frac{|S_1 - S_2|}{|Y_1 - Y_2|}. \quad (1)$$

Here, Y_n represents the two different measured admittances on the sample or during the retraction scan, whereas S_n stands for the S-parameter measured at the respective standard or during a retraction scan. This assumes a calibrated VNA. Often, it is enough to use the factory settings because they let the VNA appear to be roughly calibrated.

In this paper, two types of matching networks are investigated. LNE and Lille use interferometry based matching networks, whereas METAS and JKU use matching networks which are put in between tip and VNA. For this latter type, assume that the capacity at the tip is C_{tip} and the operating frequency is f . Then the admittance of the tip capacity is

$$Y = j2\pi f C_{tip}. \quad (2)$$

The reflection coefficient of this admittance is

$$\Gamma = \frac{1/Y - 50\Omega}{1/Y + 50\Omega}. \quad (3)$$

For small tip capacitances, one can approximate this as

$$\Gamma \approx 1 - 100\Omega * Y. \quad (4)$$

Note that this approximation yields a reflection coefficient magnitude larger than one. While this is not physically possible, it poses no problem for the following calculations. Using (4) with (1), one can show that the gain of a lossless system without a matching network would be 100 per Siemens. Now a matching network is inserted between the tip and the VNA. The matching network can be described by its four S-parameters S_{xyM} and converts the reflection coefficient to

$$\Gamma_M = S_{11M} + \frac{S_{21M}S_{12M}\Gamma}{1 - S_{22M}\Gamma}. \quad (5)$$

Here it is obvious that the gain of the network is defined by the fraction in (5). Using passive networks constrains $|S_{12M}|$ and $|S_{21M}|$. In other words, the largest signal can be expected when the term $|1 - S_{22M}\Gamma|$ is minimized. Thus, the product $S_{22M}\Gamma$ needs to be as close to one as possible. This translates to minimizing losses in the matching network and between the matching network and tip. In practice, it is difficult to make exact predictions from manufacturer specifications of components on gain because very tiny amounts of loss can have a large influence on the gain.

Interferometric matching networks require a different gain calculation. For simplicity, one assumes that all components do not have reflections. The measured signal at the VNA is then

$$\Gamma_{MI} = (A_{divider}A_{coupler}\Gamma + CS)A_{amp}. \quad (6)$$

Here $A_{divider}$, $A_{coupler}$, CS , and A_{amp} denominate divider attenuation, coupler attenuation, cancellation signal, and amplification, respectively. The cancellation signal is usually set such that the input of the amplifier is close to zero. The quantities in (6) are obtained from the components respective data sheets: $A_{divider} = 0.447$, $A_{coupler} = 0.32$, and $A_{amp} = 56.23$. Note that the amplifier has 25 dB minimum amplification with ± 5 dB flatness. Inserting these numbers into (6) and plugging this into (1) yields a gain of 804 per Siemens. Reflections, resonances, and unaccounted losses between the components can lower or increase this gain.

In order to characterize the noise, one would lift the tip high above the sample and do a scan in air. This yields the noise of the complete electrical system, including VNA and matching network. Note that the translation of mechanical noise to electrical noise is strongly attenuated by lifting the tip. Consequently this part is missing in what is called here noise of the complete setup N_C . By calculating the variance and standard deviation of the data, one gets the noise

$$N_C = \sqrt{\text{var}(S)}. \quad (7)$$

Here S stands for the raw S-parameters in each pixel of the image scanned in air. Another way to obtain the noise of the complete system would be to fit a polynomial of higher order (here, order 5) into the raw S-parameters of a retraction curve

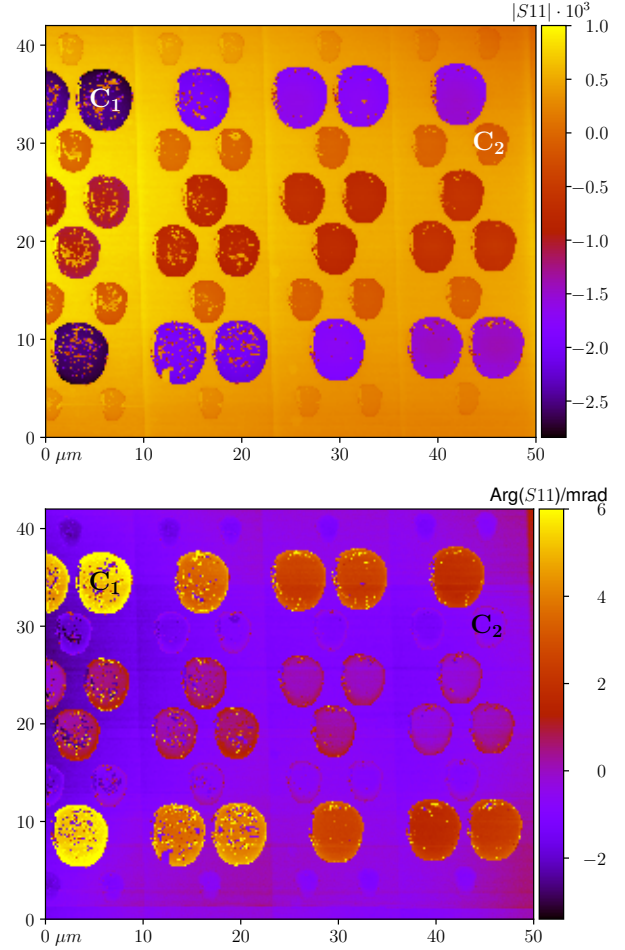


Fig. 5. Measurement results of a sample containing micro disc capacitors from MC2 Technologies. Upper and lower panel show raw results in amplitude and phase in radian. The intermediate frequency bandwidth is set to 500 Hz. The raw results have been flattened with a second order polynomial and a plane has been subtracted.

and thus extract the noise of the VNA and matching network by taking the difference between the polynomial and measured data. Again here the noise does not contain the part which translated from mechanical noise to electrical noise.

In the last step, one needs to characterize the noise of the VNA. This can be done as proposed in VNA Tools framework [5], or just by connecting short circuits to the VNA ports, and measuring the noise in S_{21} data, which yields the noise floor N_F , and the noise in S_{11} , which yields the trace noise in amplitude N_{TA} and phase N_{TP}

$$N_F = \sqrt{\text{var}(S_{21})} \quad (8)$$

$$N_{TA} = \sqrt{\text{var}(|S_{11}|)} \quad (9)$$

$$N_{TP} = \sqrt{\text{var}(\text{arg}(S_{11}))}. \quad (10)$$

The noise contribution of the VNA per measurement is

$$N_{VNA} = \sqrt{N_F^2 + N_{TA}^2 |S_m|^2 + |S_m|^2 N_{TP}^2} \quad (11)$$

where the mean of the S used in (7) defines $S_m = \bar{S}$. The noise of the VNA needs to be subtracted from the complete

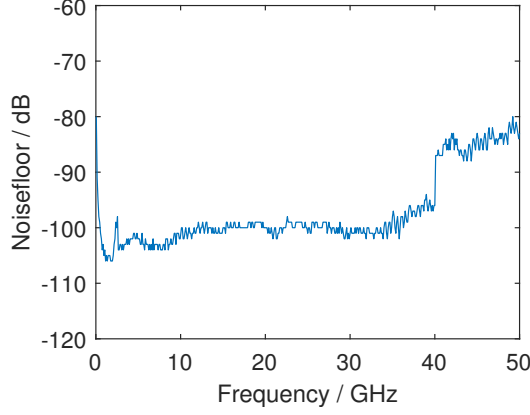


Fig. 6. Noise floor in dB of a Rohde Schwarz ZNA 50 with 500 Hz intermediate frequency bandwidth.

noise N_C in order to obtain the noise of the matching network

$$N_M = \sqrt{N_C^2 - N_{VNA}^2}, \quad (12)$$

which is always real because $N_C > N_{VNA}$. Now each matching network can be characterized by its gain G and by its added noise N_M .

III. RESULTS

A. METAS result

At METAS, this technique has been applied to an SMM with a Beatty line as a matching network attached to it. The in [6] described sample containing micro-capacitors has been used for determining the gain. In fig. 5, one can see the absolute value of raw S_{11} and phase measured at 2.158 GHz. Similar results have been obtained at 3.62 GHz and 5.395 GHz. The top leftmost capacitor with an assumed radius of $2 \mu\text{m}$ and a silicon oxide height of 50 nm and the rightmost capacitor in the second row with a radius $1 \mu\text{m}$ and an oxide height of 200 nm have been used as references. The top leftmost capacitor has a capacitance of $C_1 = 9.52 \text{ fF}$ and the rightmost second row capacitor has $C_2 = 0.86 \text{ fF}$ assuming a relative permittivity of $\epsilon_{\text{SiO}_2} = 3.9$ and using the equations given in [7]. Note that not the largest possible difference between capacities is used because this would involve using a very small capacitor with added measurement uncertainties. Evaluating the image at the positions of the chosen capacitors yields the gain per nS given in table II.

The noise floor and trace noise of the VNA are measured, and the noise of the complete system consisting of VNA and matching network is measured in order to determine the amount of added noise by the matching network. The results of complete noise N_C , VNA noise N_{VNA} , and added noise N_M are given in table I. Measuring the noise floor of the VNA yielded the results depicted in fig. 6.

B. JKU result

At JKU, combined retraction scans of electric force microscopy (EFM) and SMM of the metallic tip over a gold

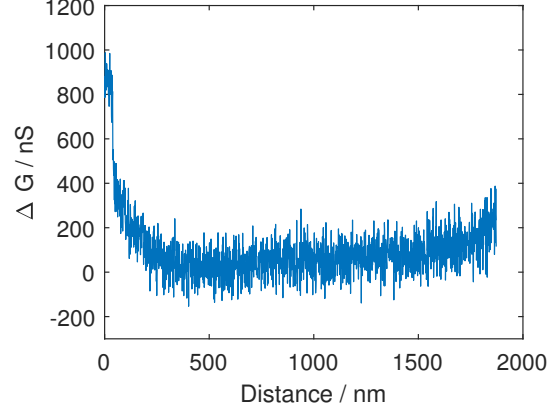


Fig. 7. The difference of admittance plotted over the distance between sample and tip at 3 GHz with a tuner as impedance match attached.

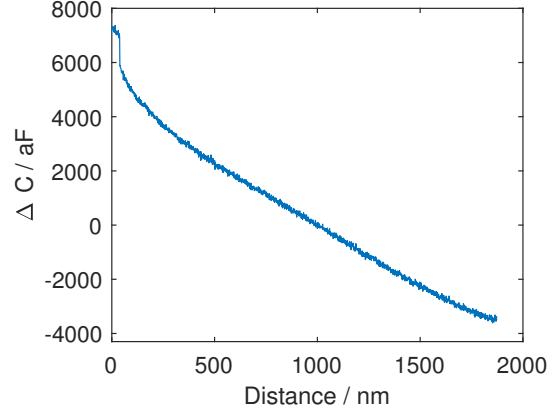


Fig. 8. The difference of capacitance plotted over the distance between sample and tip at 3 GHz with a tuner as impedance match attached.

surface have been used to obtain calibrated values for the tip sample capacitance and to obtain values for the associated S-parameters. During the retraction scan, a signal with a low frequency ω in the kHz range is applied to the tip and sets the tip into motion. The motion can be measured with a lock-in amplifier; see also [8]. The relation between the electrostatic force, F_{es} , and the tip-sample capacitance, C is

$$F_{es} = \frac{1}{4} \frac{dC}{dz} V_0^2 \cos(2\omega t) \quad (13)$$

The electrostatic force can be converted into the voltage normalized force

$$\frac{dC}{dz} = \frac{2F_{es,2\omega}}{V_0^2} \quad (14)$$

that corresponds to the capacitance gradient with respect to the tip-sample distance, z . Integrating this curve gives the desired tip-sample capacitance, $C(z)$, and the impedance, $Z(z)$, for calibrating the SMM. Once the SMM is calibrated, using the mSOL calibration technique and impedances $Z(z)$ as standards, one can obtain calibrated retraction curves in S_{11} and convert these into calibrated retraction curves in conductivity and capacitance; see figs. 7 and 8.

The gain is extracted from measurements at z -positions of approximately 1 nm and 1800 nm. The extracted gain of the setup with the tuner at 3 GHz is given in table II, and the noise is shown in I. For comparison, measurements at two frequencies (8 GHz and 28 GHz) of the same setup without the tuner are given. For the noise measurement, it was found that the routines provided by VNA Tools are not suitable because the setup shows some short-term drift. This is interpreted by VNA Tools as noise and leads to a seemingly very high noise contribution from the VNA itself. In order to have a more realistic result, here the VNA is neglected as a noise source and the complete noise of the VNA and matching network is measured.

C. LNE and University of Lille result

At LNE and the University of Lille, the noise of the complete setup, free from the sample's influence, is measured before estimating the added noise. To this end LNE recorded the S_{11} parameter at several tip-sample separation distances and determined the corresponding values of the resonance frequency f_0 . Figure 9 shows that f_0 increases with the tip-sample distance and reaches a plateau at a distance of 1000 μm . No further changes in f_0 were observed as the distance increased. Therefore, the tip-sample distance of 1000 μm was considered the critical separation distance above which the influence of the sample on the measured S_{11} parameter vanishes. Consequently, at LNE and the University of Lille the

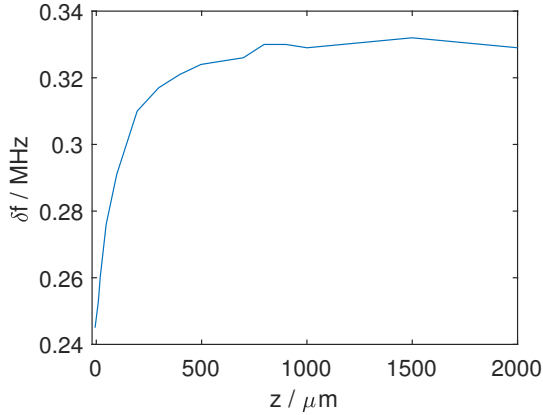


Fig. 9. Resonance peak frequency of S_{11} parameter as a function of tip-sample distance.

complete electrical noise N_C for each scan frequency is acquired by placing the probe at a tip-sample separation distance greater than 1000 μm . Furthermore, the noise floor and the trace noise are recorded using the VNA Tools framework with two short circuit standards (HP85052-60006 and MMC8047F F791). At LNE the equivalence of the short standards for noise characterization has been verified by exchanging the standards between port one and two. Finally, the noise associated with the setups is computed using equations (7-12). The results are shown in table I. As LNE and the University of Lille use interferometric systems in their setups, the output signal is amplified, and therefore there is the possibility to saturate the

TABLE I
NOISE OF SMM SETUPS

	Frequency in GHz	2.158	3.62	5.395
METAS	N_C	-85.63 dB	-82.18 dB	-77.75 dB
	N_{VNA}	-102.65 dB	-102.14 dB	-98.32 dB
	N_M	-85.72 dB	-82.22 dB	-77.78 dB
	Frequency in GHz	3	8	28
JKU	N_C	-89 dB	-95 dB	-79 dB
	Frequency in GHz	2.13	4.54	5.42
LNE	N_C	-64.60 dB	-59.67 dB	-64.04 dB
	N_{VNA}	-94.77 dB	-93.99 dB	-94.70 dB
	N_M	-64.60 dB	-59.67 dB	-64.05 dB
	Frequency in GHz	13.81	15.89	18.94
LNE	N_C	-65.33 dB	-72.70 dB	-67.68 dB
	N_{VNA}	-95.68 dB	-95.92 dB	-95.92 dB
	N_M	-65.34 dB	-72.72 dB	-67.69 dB
	Frequency in GHz	2.16	4.465	
Lille	N_C	-43.26 dB	-49.91 dB	
	N_{VNA}	-94.87 dB	-97.00 dB	
	N_M	-43.26 dB	-49.91 dB	

receivers of the VNA. To stay below the saturation region, LNE uses an attenuator in their setup. SMM scans were acquired at different frequencies on an MC2 sample, and the attenuator was adjusted until the capacitance obtained by the mSOL calibration differed by less than 5% from the computed standard values [6]. The attenuator is set to 7 dB for f_{VNA} below 6 GHz and to 21 dB for f_{VNA} above 10 GHz. LNE also used these images of MC2 samples to extract the gain of the matching network. In particular the capacitors with radii $R = 4.1 \mu\text{m}$, $R = 1.14 \mu\text{m}$ and oxide heights $h = 53.1 \text{ nm}$, $h = 204.4 \text{ nm}$ are used for this. The University of Lille used as well an MC2 sample to determine the gain and did not account for possible saturation of the VNA receivers. In particular two capacitors are used with radii $R = 1.75 \mu\text{m}$, $R = 0.675 \mu\text{m}$ and oxide heights $h = 64.4 \text{ nm}$, $h = 369.4 \text{ nm}$.

TABLE II
GAIN PER S OF SMM SETUPS

METAS			
Frequency in GHz	2.158	3.62	5.395
Gain per S	44.4	111.1	260.5
JKU			
Frequency in GHz	3	8	28
Gain per S	105	177	242
LNE			
Frequency in GHz	2.13	4.54	5.42
Gain per S	309.8	736.6	897.1
Frequency in GHz	13.81	15.89	18.94
Gain per S	4018.6	9504.7	7906.6
Lille			
Frequency in GHz	2.16	4.465	
Gain per nS	1030	620	

In table III the best noise of each matching network at each institution is listed with $k = 1$. This is the uncertainty contribution from the matching network which one would have to add on all measurement results. As said before, the translated mechanical noise and the noise from the VNA would have to be quadratically added to this for a complete picture.

TABLE III
BEST NOISE OF IMPEDANCE MATCHING SETUP

Setup	Noise in S
METAS 5.395 GHz	5e-7
JKU 28 GHz	1e-7
LNE 18.94 GHz	2.4e-8
Lille 4.465 GHz	5e-6

IV. CONCLUSION

The interferometric setups require two-port VNAs and more hardware, whereas the one-port setups (Beatty line and tuner) require less hardware. On the other hand, the two port networks offer more possibilities for setting signal amplitudes. The achievable signal-to-noise ratios are similar with both techniques. Stability is another important factor for metrology applications. Here, it is better to have a setup without additional active elements and with as few components as possible. On the other hand, such a stable network has a lower signal to noise ratio than a more complicated one.

ACKNOWLEDGEMENTS

This project (EMPIR 20IND12 ELENA) has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme. One of the authors thanks Alexis Litwin for technical support.

REFERENCES

- [1] M. Randus and K. Hoffmann, "A novel method for direct impedance measurement in microwave and mm-wave bands," in *75th ARFTG Microwave Measurement Conference*. IEEE, 2010, pp. 1–5.
- [2] S.-S. Tuca, M. Kasper, F. Kienberger, and G. Gramse, "Interferometer scanning microwave microscopy: Performance evaluation," *IEEE Transactions on Nanotechnology*, vol. 16, no. 6, pp. 991–998, 2017.
- [3] M. Horibe and I. Hirano, "Demonstrations of rf impedance matching techniques for near-field scanning microwave microscopy based on atomic force microscopy," in *2017 90th ARFTG Microwave Measurement Symposium (ARFTG)*. IEEE, 2017, pp. 1–4.
- [4] J. Hoffmann, S. de Preville, B. Eckmann, B. Herzog, K. Haddadi, G. Gramse, D. Richert, and F. Piquemal, "Comparison of impedance matching networks for scanning microwave microscopy," in *Conference on Precision Electromagnetic Measurements CPEM*. IEEE, 2022, pp. 1–2.
- [5] M. Wollensack and J. Hoffmann, "Metas vna tools ii-math reference v1." 2013.
- [6] F. Piquemal, J. Morán-Meza, A. Delvallée, D. Richert, and K. Kaja, "Progress in traceable nanoscale capacitance measurements using scanning microwave microscopy," *Nanomaterials*, vol. 11, no. 3, p. 820, 2021.
- [7] G. Sloggett, N. Barton, and S. Spencer, "Fringing fields in disc capacitors," *Journal of Physics A: Mathematical and General*, vol. 19, no. 14, p. 2725, 1986.
- [8] G. Gramse, M. Kasper, L. Fumagalli, G. Gomila, P. Hinterdorfer, and F. Kienberger, "Calibrated complex impedance and permittivity measurements with scanning microwave microscopy," *Nanotechnology*, vol. 25, no. 14, p. 145703, 2014.