Czech Technical University in Prague

DOCTORAL THESIS STATEMENT

Czech Technical University in Prague

Faculty of Electrical Engineering
Department of Electromagnetic Field

METHODS FOR MEASUREMENT OF EXTREME IMPEDANCES

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The defence of the doctoral thesis will be held on __________ at ________ before the Board for the Defence of the Doctoral Thesis in the branch of study Radioelectronics in the meeting room No. ________ of the Faculty of Electrical Engineering of the CTU in Prague.

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Contents

Section 1

Current Situation of the Studied Problem

Desire to make electronic circuits capable of operation at higher frequencies and higher data rates, and effort to make them small enough to place a complex system into a single integrated circuit lead to nanoscale systems. In the last decade attention of engineers is being drawn by new components that are very promising for high-frequency and high-speed electronic circuits. These new elements are carbon nanotubes (CNTs) [1, 2, 3, 4], graphene cylinders with diameter in orders of nm. They are seen as future successors of contemporary semiconductors, because of their very interesting properties. For instance, the mean free path of an electron in a carbon nanotube at room temperature may be in orders of $\sim 100\,\mathrm{nm}$ [5, 6].

However, devices based on carbon nanotubes (transistors, logic gates, sensors, etc.) exhibit impedances in orders of tens and hundreds of $\mathrm{k\Omega}$, that causes extreme impedance mismatch with current high-frequency measurement equipment with $50\,\Omega$ system impedance.

As all the impedance measurements at microwave frequencies are done by measuring a reflection coefficient, from which the desired value of the corresponding impedance is calculated, it is almost impossible to characterize these devices by common measurement equipment, because the measured reflection coefficient is very insensitive quantity for very low and very high impedances [7, 8]. In other words, even small error in the measured reflection coefficient may cause extreme errors in the calculated value of the corresponding impedance. From this point of view we further address impedances significantly lower or significantly greater than the $50\,\Omega$ system impedance as extreme impedances.

The situation is depicted in Fig. 1.1, which illustrates the dependence of the measured reflection coefficient Γ_x on value of purely real impedance $Z_\mathrm{x} = R_\mathrm{x} + \mathrm{j}0$ of a device under test (DUT). It can be clearly seen that the reflection coefficient Γ_x is very insensitive quantity for impedances lower than about $1\,\Omega$ and greater than about $10\,\mathrm{k\Omega}$.

Broadband measurement of extreme impedances is to such an extent undiscovered area as there are only a very few papers dealing with such measurements. Several publications [7, 9] describe a method for measurement of extreme impedance of a scanning probe tip of a scanning capacitance microscope. However, the method is based on detuning of a half-wavelength coaxial resonator by small changes of tip capacitance, and

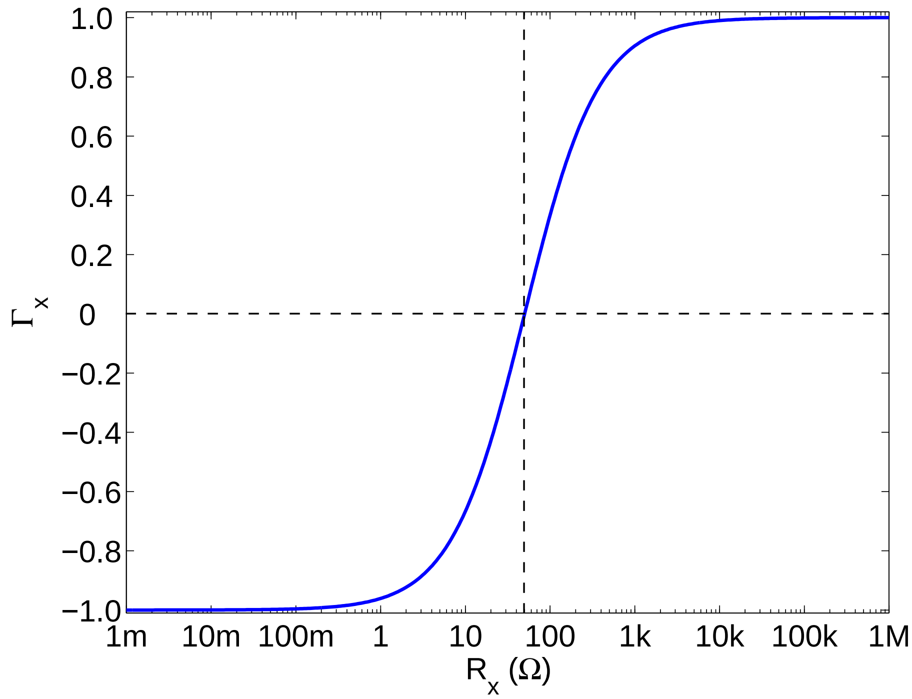


Figure 1.1: Dependence of the measured reflection coefficient Γ_x on value of purely real impedance $Z_\mathrm{x} = R_\mathrm{x} + \mathrm{j}0$ of a device under test.

thus can be hardly applied for broadband measurements.

Publications dealing with practical measurements of extreme impedances, especially carbon nanotubes, are merely focused on overcoming the problem by using common measurement methods with emphasis on precise calibration and deembedding techniques [10, 11], measurement of thousands of high-impedance devices in parallel [12] or performing only relative measurements [13, 14], instead of developing new instrumentation.

A method for measurement of extreme impedances developed at NIST (National Institute for Standards and Technology), Boulder, Colorado, USA, introduced in December 2008 [15], is an extension of our measurement method introduced one year earlier in November 2007 [16], which is described in Subsection 4.1. However, the authors did not bring any clear evidence how their measurement method improves measurement accuracy or stability.

Section 2

Objectives of the Doctoral Thesis

The main objective of the doctoral thesis is development of a new measurement method that in comparison with the currently known measurement methods improves measurement accuracy and precision for broadband high-frequency measurement of very high and/or very low impedances and its experimental verification.

Section 3

Working Methods

A detailed analysis of current high-frequency impedance measurement methods was performed from the point of view of measurement of extreme impedances. Based on this knowledge a basic principle of operation of a novel measurement method was developed. The method is further addressed as nearly balanced bridge measurement method and it is discussed in Subsection 4.1.

The new method employs a commercial vector network analyzer (VNA) to which a developed hardware extension unit is connected. This arrangement then represents a measurement system for microwave measurement of extreme impedances.

The developed measurement method was completely mathematically described. A suitable error model and a corresponding calibration and correction method were developed, equations for calculation of the maximal applicable gain of the amplifier were derived and estimation of upper bound for measurement error was calculated as well. Possibilities of alternative realizations of the extending network and biasing of the DUT were discussed.

After that, a real measurement sytem was assembled and tested. The measurement system was verified from the point of view of measurement stability improvement, where long-term fluctuations of the measured value of impedance of a DUT were examined and compared against results obtained from a classical measurement method of impedance measurement by a VNA. Subsequently, a measurement of extreme impedances of SMD resistors ranging from $12\,\mathrm{k}\Omega$ up to $330\,\mathrm{k}\Omega$ was performed.

After successful experimental verification of this method another method, mostly based on the principles of the nearly balanced bridge measurement method, was derived. The new method is further adressed as the method for direct impedance measurement and it is discussed in Subsection 4.2. Similarly as in the case of the preceding method the new method was completely mathematically described. A measurement sytem was assembled from very broadband components. A broadband measurement of open end and short terminations were performed as well as a narrowband frequency-sweep measurement of a resonance loop of a cylindrical dielectric resonator. The results were compared against the results of the the classical measurement method.

Section 4
Results

Two novel measurement methods for measurement of extreme impedances – the nearly balanced bridge measurement method and the method for direct impedance measurement – were developed and successfully experimentaly verified.

4.1 Nearly Balanced Bridge Measurement Method

The proposed method is based on adding or subtracting of a reference reflection coefficient Γ_{ref}, corresponding to a reference impedance Z_{ref}, to or from the reflection coefficient Γ_{x} of the DUT with impedance Z_{x} by a passive four-port network, amplifying the small differential signal by an amplifier and measuring the resulting signal by a common VNA as a transmission coefficient t_{21}. An arrangement of the measurement system is depicted in Fig. 4.1. The passive four-port network is usually a 180-degree or a 90-degree 3 dB hybrid coupler.

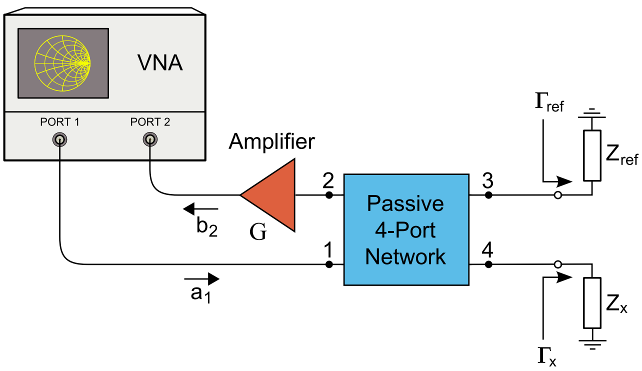


Figure 4.1: Arrangemet of the measurement system implementing the nearly balanced bridge measurement method.

Fig. 4.2 shows measurement stability improvement. It depicts spreading of 3201 consequent values of the corrected reflection coefficient Γ_{x} of an SMA female connector open end (i.e. high-impedance DUT) around the average at frequency 1.57 GHz, that were acquired during 94-minute period under stable conditions with 1 Hz IF bandwidth.

It was determined that 99 % of the points Γ_{x} lie inside a circle with a diameter of 258.79×10^{-6} in the case of the classical method and 9.38×10^{-6} in the case of the proposed method, centered at the average value. That represents more than 27-times reduction of the diameter, and thus 27-times better measurement stability, compared

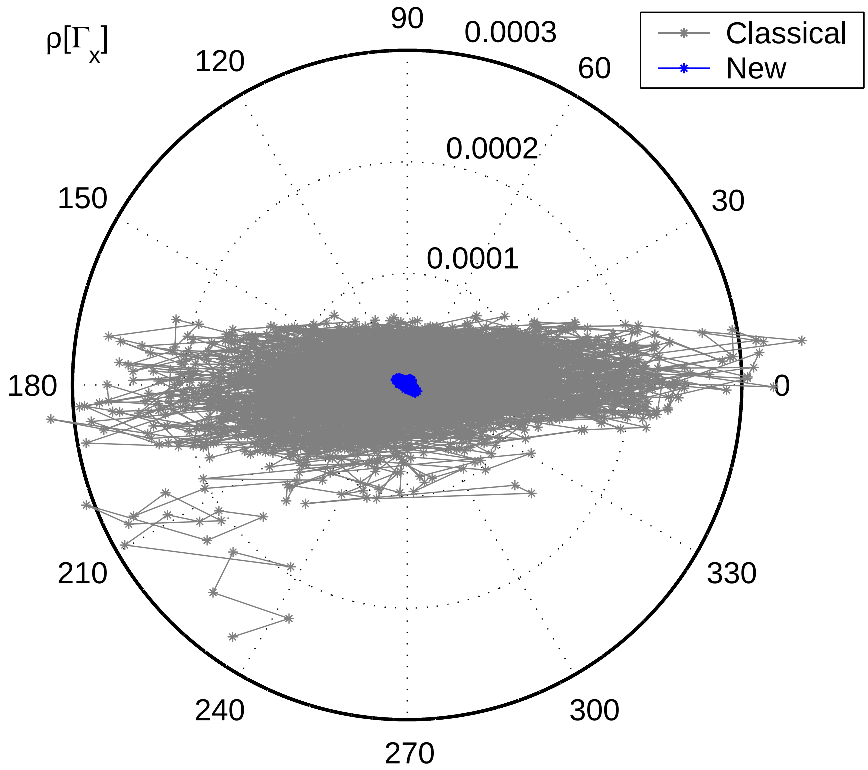


Figure 4.2: Spreading of the 3201 values of the corrected reflection coefficient Γ_x of the SMA female connector open end (i.e. high-impedance DUT) around the average value calculated at frequency 1.57 GHz under stable conditions for the classical one-port reflection coefficient measurement method ("Classical") and the proposed measurement method ("New").

with the classical one-port reflection coefficient measurement method, which very well correspond with theoretical assumptions regarding the gain of the used amplifier.

Table 4.1 shows results of measurement of SMD resistors of size 0603 with extreme impedance values ranging from 12 kΩ up to 330 kΩ. SMD resistors 11 kΩ, 75 kΩ and 1 MΩ of the same physical dimensions were used as the calibration standards. The calibration standards were described as purely resistive impedances by their DC resistance. Therefore, the parasitics of the SMD resistors (inductances, capacitances) became an integral part of the error model and they were eliminated by the calibration and measurement correction. Thus, in ideal case, when the parasitics of all the SMD resistors are exactly the same and the placement is absolutely repeatable, the measured values of impedances of the resistors can be expected to be purely real impedances equal to their DC resistance. The results exhibit reasonable agreement between the measured values of extreme impedances and the DC resistance values of the SMD resistors up to 240 kΩ. However, for higher resistor values the measured impedances differ significantly from the supposed (DC) values that is dominantly caused by a limited connection reproducibility of the used test fixture. Properties of the measurement method for general complex impedances are illustrated by a calculated corresponding conformal map in Fig. 4.3.

DUT / Cal. Std. Number	DC Resistance (kΩ)	Measured Impedance	
		Re $[Z_x]$ (kΩ)	Im $[Z_x]$ (kΩ)
Cal. Std. #1	11.00	-	-
1	12.01	13.16	1.13
2	12.97	13.45	−0.21
3	16.08	14.84	−0.79
4	18.57	19.17	−2.70
5	22.23	24.90	−0.83
6	26.87	31.18	1.15
7	34.08	35.88	0.09
8	42.50	38.45	3.82
9	52.10	56.56	11.01
10	62.10	61.66	12.26
Cal. Std. #2	75.70	-	-
11	90.70	92.74	3.58
12	99.30	79.43	−11.56
13	150.20	132.50	−4.12
14	239.70	208.80	−6.79
15	329.50	202.36	323.39
Cal. Std. #3	1004.00	-	-

Table 4.1: Results of the SMD resistors measurement at frequency 1.80 GHz.

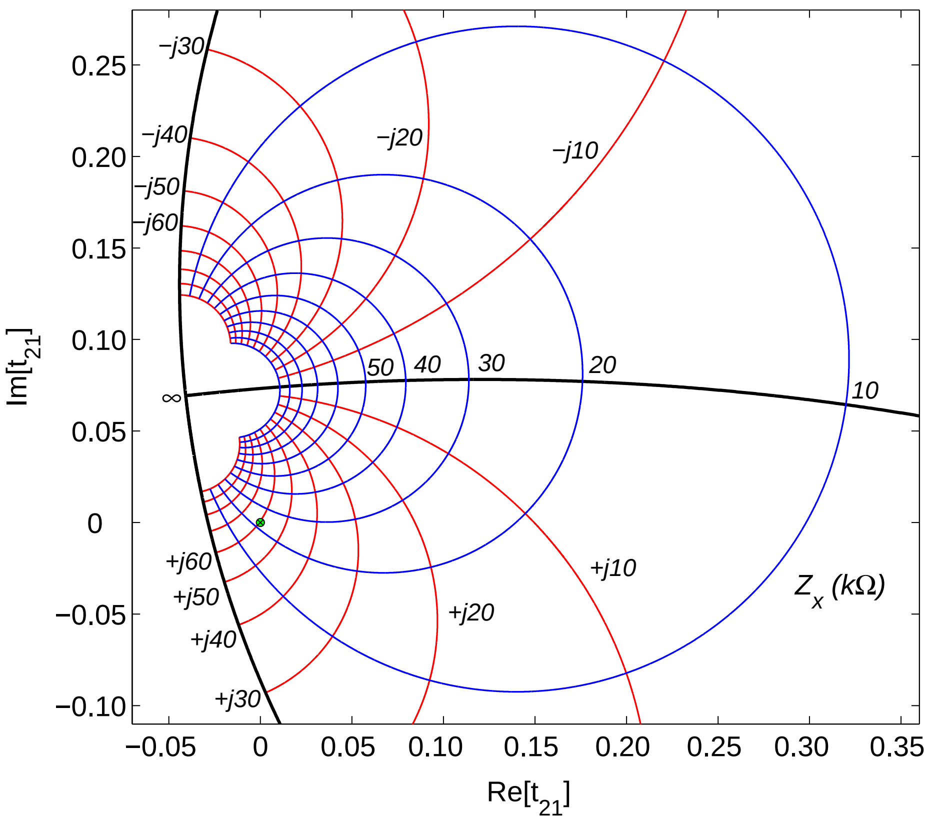


Figure 4.3: Conformal map – impedance grid for the input impedance Z_x of the DUT in the complex plane of the measured transmission coefficient t_{21} at frequency 1.80 GHz for impedances Z_x ranging from 10 kΩ up to 100 kΩ, or ∞, with step 10 kΩ.

4.2 Method For Direct Impedance Measurement

The method for direct impedance measurement represents an extension of the nearly balanced bridge measurement method. The method differs in principle of deriving the reference signal. Unlike the nearly balanced bridge measurement method, where the reference signal is derived by a power divider inside the VNA and a transmission coefficient is measured, in the case of the proposed direct method the reference signal is derived by a passive network similarly as the testing signal and a ratio of the two received waves b_2 and b_3 is measured. An arrangemet of the measurement system is depicted in Fig. 4.4.

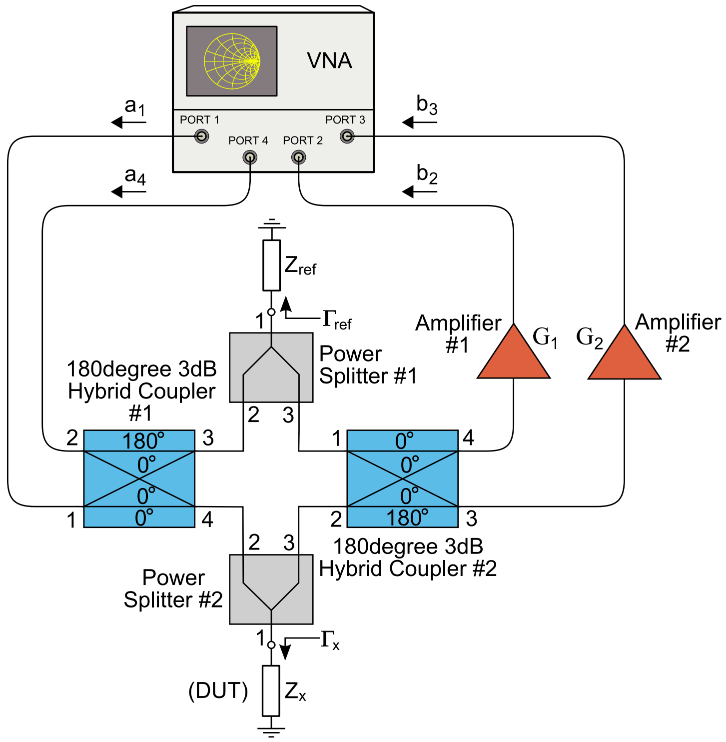


Figure 4.4: Arrangement of the measurement system implementing the direct method for impedance measurement based on a pair of 180-degree 3 dB hybrid couplers.

The method is based on simultaneous adding and subtracting the reference reflection coefficient Γ_{ref}, corresponding to a reference impedance Z_{ref}, and the reflection coefficient Γ_{x} of the DUT with impedance Z_{x} by a passive network, amplifying the two signals by amplifiers and measuring their resulting mutual ratio

$$W_{ij,\,k} = \left.\frac{b_i}{b_j}\right|_{a_k \neq 0,\; a_n = 0\; \forall n \neq k} = \frac{1}{W_{ji,\,k}}. \tag{4.1}$$

by a common VNA.

In ideal case the measured ratio is directly proportional to the impedance or admittance of the DUT depending on the reference impedance. For instance, in case the reference impedance is chosen as ideal open end ($\Gamma_{\text{ref}} = 1$) and assuming ratio $W_{23,\,1}$ the

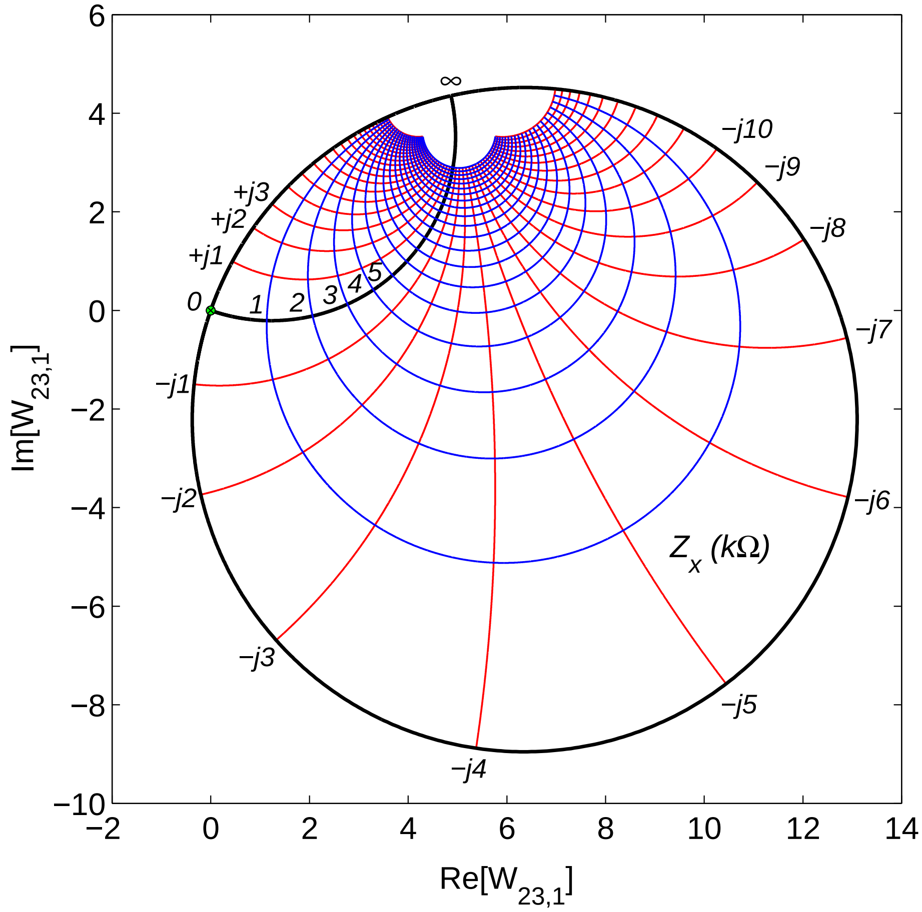


Figure 4.5: Conformal mapping – impedance grid for the input impedance Z_x of the DUT in the complex plane of the measured ratio $W_{23,1}$ at frequency 3.73 GHz for impedances Z_x ranging from 0 Ω up to 20 kΩ, or ∞, with step 1 kΩ.

ratio is directly proportional to the impedance of the DUT since

$$W_{23,1} = \frac{G_1}{G_2}\frac{(\Gamma_{\text{ref}} + \Gamma_x)}{(\Gamma_{\text{ref}} - \Gamma_x)} = \frac{G_1}{G_2}\frac{(1 + \Gamma_x)}{(1 - \Gamma_x)} = \frac{G_1}{G_2}\frac{Z_x}{Z_0}. \tag{4.2}$$

The measurement system can be used for measurement of both high and low impedances depending on the active source port of the VNA without changing the hardware configuration.

Impedance conformal map in the complex plane of the measured ratio $W_{23,1}$ is depicted in Fig. 4.5.

Fig. 4.6 shows measurement stability improvement and noise rejection. It depicts spreading of 1601 consequent values of the corrected reflection coefficient Γ_x of an SMA female connector open end (i.e. high-impedance DUT) around the average at frequency 1.57 GHz, that were acquired during 1.48 seconds under stable conditions with 1 kHz IF bandwidth. Radius of the area where 99 % of the points lie was 2.4×10^{-3} in the case of the classical method and 1.9×10^{-4} in the case of the proposed method. That represents more than 12-times improved stability of the corrected values, which fairly

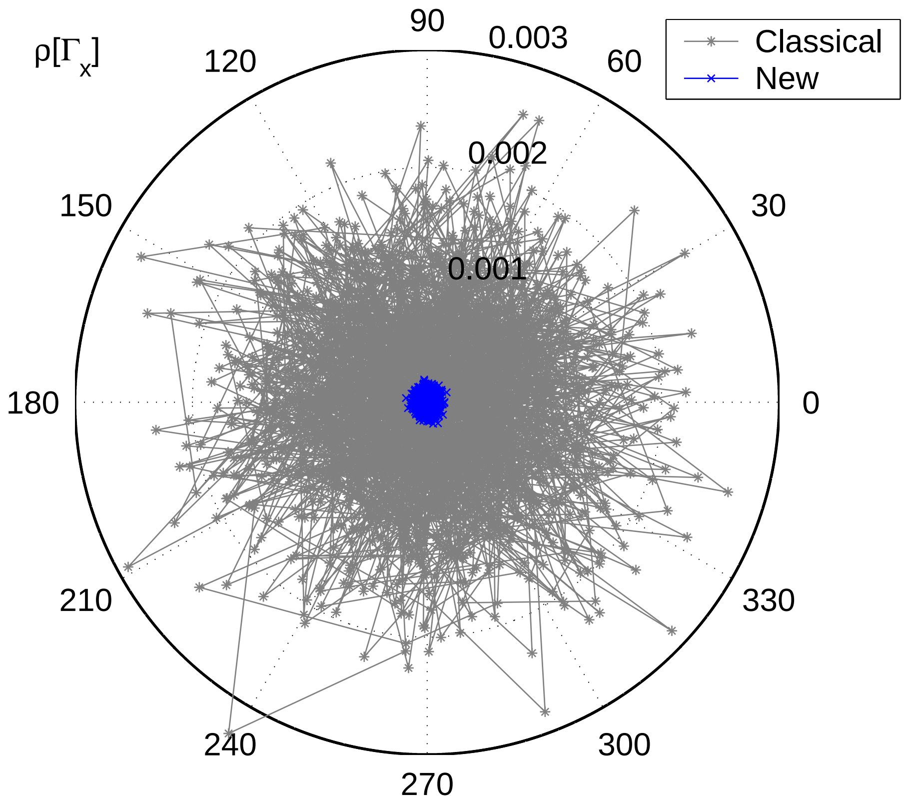
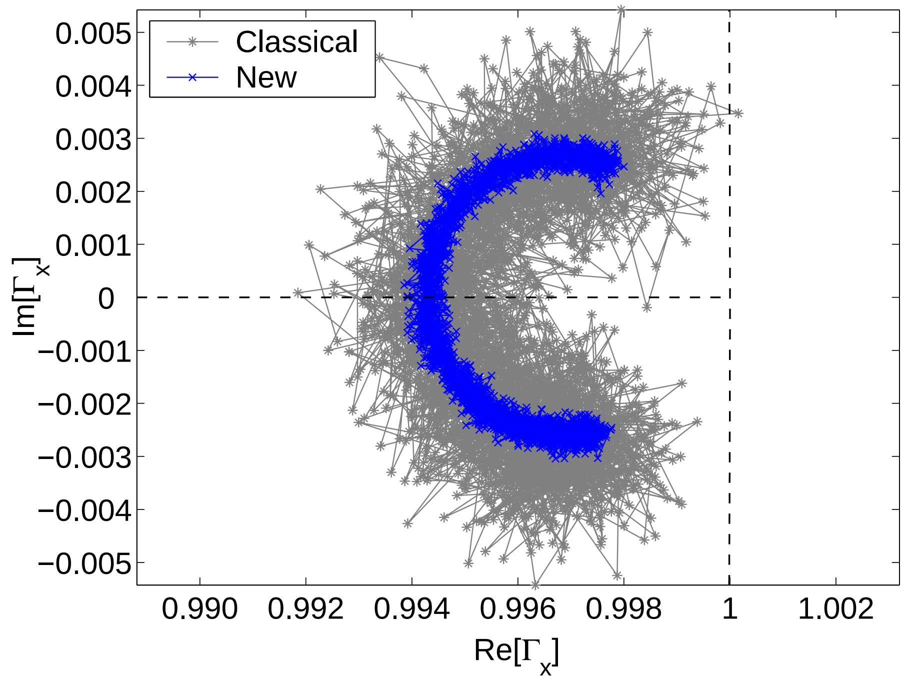


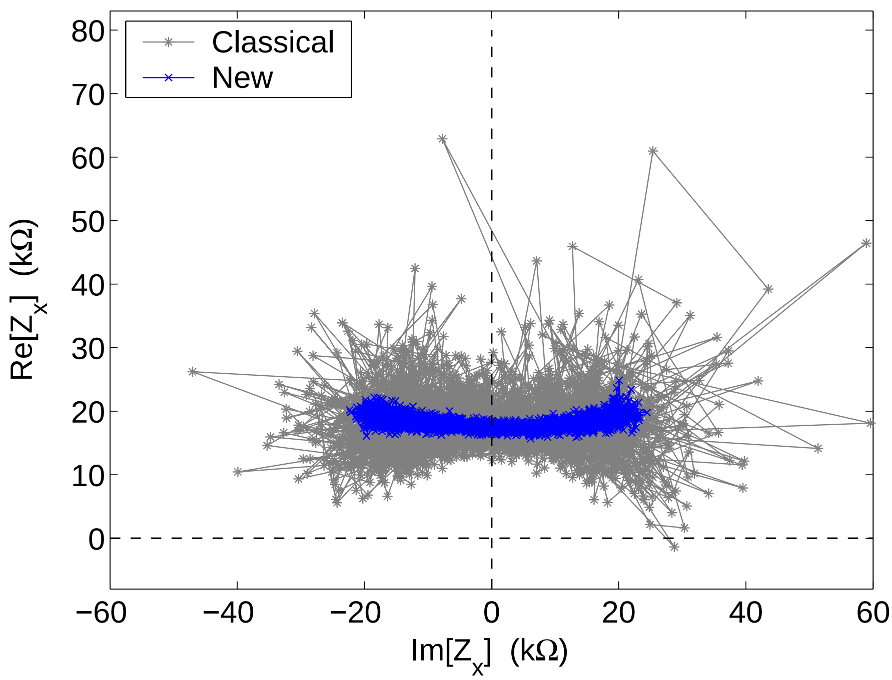
Figure 4.6: Comparison of spreading of the 1601 values of the corrected reflection coefficient Γ_x of the open end of the SMA female connector (i.e. high-impedance DUT) around the average value at frequency 1.57 GHz under stable conditions for the classical one-port reflection coefficient measurement method ("Classical") and for the proposed measurement method ("New").

well corresponds with theoretical assumptions regarding the gain of the amplifier.

Fig. 4.7 show deembedded frequency sweep measurement of a dielectric resonator excited from open end of APC-7 connector in frequency range from 6.04 GHz to 6.06 GHz. It can be clearly seen that the proposed measurement method provides more resolution. The advantage of the proposed method is much more obvious if we look at the impedance Z_x instead of the reflection coefficient Γ_x (Fig. 4.7b). Values of the measured impedance varies with frequency roughly from $(19 - \mathrm{j}22)$ kΩ to $(19 + \mathrm{j}22)$ kΩ. For instance, it can be clearly seen that when using the proposed measurement method the noise causes variations in the real part of the impedance Z_x (y-axis in Fig. 4.7b) of about 2.5 kΩ with maximal peak difference of 5.8 kΩ. On the contrary, the classical measurement method exhibits variations of about 10.1 kΩ with maximal peak difference of 43.9 kΩ. That makes the classical measurement method in this case useless for such measurements in the high-impedance region.



(a) Measured points of the reflection coefficient Γ_x after deembedding. The vertical dashed curve represents edge of the Smith chart $|\Gamma_x| = 1$. The reflection coefficient moves clock-wise with frequency.



(b) Corresponding points of the measured impedance Z_x after deembedding. Y-axis represents the real part of the impedance Z_x.

Figure 4.7: Results of dielectric resonator measurement obtained from the classical measurement method and the proposed method for power level −40 dBm at the reference plane of measurement and 1 kHz IF bandwidth of the VNA. Total number of 2560 frequency points was acquired during single frequency sweep in frequency range from 6.04 GHz to 6.06 GHz.

Section 5
Conclusion

The doctoral thesis has brought following results:

1. A detailed analysis of current measurement methods for impedance measurement in microwave frequency region was done from the point of view of measurement of extreme impedances.

2. Based on this knowledge two novel measurement methods were developed – the nearly balanced bridge measurement method discussed in Subsection 4.1 and the method for direct impedance measurement discussed in Subsection 4.2.

3. These two novel methods were completely theoretically described including the calibration process, error models and calculation of the maximal applicable gain of the amplifiers.

4. The methods were successfully experimentally verified and the measurements were compared against the results obtained from classical widely used method for reflection coefficient measurement using the VNA. The results clearly proved that the developed measurement methods significantly improve measurement stability and accuracy for extreme impedances measurements.

5. Possibilities of DC biasing of the DUT and the reference impedance were analyzed and discussed.

6. A brief theoretical description how to use these two novel measurement methods for measurement of two port extreme impedance devices was given.

The objectives of the doctoral thesis have been fulfilled.

The two developed measurement methods and the obtained measurement results are unique. They significantly pushed limits of the currently used measurement methods to more and more extreme impedance values. Precise measurement of extreme impedances in orders of tens and hundreds of kΩ at microwave frequencies is now possible. And what more – there is no component used in the measurement system circuits that has, from some physical reasons, upper frequency limit (e.g. coils, transformers, etc.), since the couplers can be realized even in waveguide technology.

Although the vast majority of contemporary microwave and mm-wave applications do not necessarily need measurement of extreme impedances, in the near future we can expect expansion of technologies based carbon nanotubes as a successor of semiconductors. And then this slightly overlooked need will become very urgent.

Even today, excluding the research of devices based on the carbon nanotubes, there are needs for measurement of extreme impedances e.g. in the field of the scanning capacitance microscopy. Even companies such as Agilent Technologies and STMicroelectronics deal with development of methods for measurement of extreme impedances. In June 2011 they introduced their method for measurement of aF capacitances of MOS varactors also based on principle of subtracting two signals of similar amplitude and phase and amplifying the difference [17]. However, they did it almost four years later than us, because we described the same principle in November 2007 in [16].

List of Literature Used in the Thesis Statement

[1] P. J. Burke, "Lüttinger liquid theory as a model of the gigahertz electrical properties of carbon nanotubes," *IEEE Transactions on Nanotechnology*, vol. 1, no. 3, pp. 129–144, September 2002.

[2] P. J. Burke, Z. Yu, S. Li, and C. Rutherglen, "Nanotube technology for microwave applications," in *IEEE MTT-S International Microwave Symposium Digest*, June 2005.

[3] P. J. Burke, Z. Yu, and C. Rutherglen, "Carbon nanotubes for RF and microwaves," in *Proc. Gallium Arsenide and Other Semiconductor Application Symposium*, October 2005, pp. 1–4.

[4] W. Zhou, C. Rutherglen, and P. J. Burke, "Wafer scale synthesis of dense aligned arrays of single-walled carbon nanotubes," *Nano Research*, vol. 1, no. 2, pp. 158–165, August 2008.

[5] P. L. McEuen, M. S. Fuhrer, and H. Park, "Single-walled carbon nanotube electronics," *IEEE Transactions on Nanotechnology*, vol. 1, no. 1, pp. 78–85, 2002.

[6] D. V. Singh, K. A. Jenkins, and J. Appenzeller, "Direct measurements of frequency response of carbon nanotube field effect transistors," *Electronics Letters*, vol. 41, no. 5, pp. 280–282, 2005.

[7] H. Tanbakuchi, M. Richter, and M. Whitener, "Design of scanning capacitance microscope," in *Proc. 68th ARFTG Microwave Measurement Symposium*, Broomfield, CO, December 2006.

[8] *Impedance Measurement Handbook*, Agilent Technologies, Inc., July 2006. [Online]. Available: http://www.agilent.com

[9] H. Tanbakuchi, W. Han, and M. Richter, "Scanning impedance probe microscope," in *Proc. 8th IEEE Conf. Nanotechnology NANO '08*, 2008, pp. 218–219.

[10] P. Rice, T. M. Wallis, S. E. Russek, and P. Kabos, “Broadband electrical characterization of multiwalled carbon nanotubes and contacts,” *Nano Letters*, vol. 7, no. 4, pp. 1086–1090, 2007.

[11] D. Wang, Z. Yu, S. McKernan, and P. J. Burke, “Ultrahigh frequency carbon nanotube transistor based on a single nanotube,” *IEEE Transactions on Nanotechnology*, vol. 6, no. 4, pp. 400–403, 2007.

[12] C. Rutherglen, D. Jain, and P. J. Burke, “RF resistance and inductance of massively parallel single walled carbon nanotubes: Direct, broadband measurements and near perfect 50 Ohm impedance matching,” *Applied Physics Letters*, vol. 93, no. 8, pp. 083 119–1–3, 2008.

[13] Z. Yu, C. Rutherglen, and P. J. Burke, “Scaling of the microwave and DC conductance of metallic single-walled carbon nanotubes,” *Nanostructure Integration Techniques for Manufacturable Devices, Circuits, and Systems: Interfaces, Interconnects, and Nanosystems*, vol. 6003, no. 1, pp. 1–7, 2005.

[14] S. Li, Z. Yu, S.-F. Yen, W. C. Tang, and P. J. Burke, “Carbon nanotube transistor operation at 2.6 GHz,” *Nano Letters*, vol. 4, no. 4, pp. 753–756, 2004.

[15] A. Lewandowski, D. LeGolvan, R. A. Ginley, T. M. Wallis, A. Imtiaz, and P. Kabos, “Wideband measurement of extreme impedances with a multistate reflectometer,” in *Proc. 72nd ARFTG Microwave Measurement Symposium*, Portland, OR, December 2008.

[16] M. Randus and K. Hoffmann, “A simple method for extreme impedances measurement,” in *Proc. 70th ARFTG Microwave Measurements Conference*, Tempe, AZ, November 2007.

[17] R. Debroucke, D. Gloria, D. Ducatteau, D. Theron, H. Tanbakuchi, and C. Gaquiere, “attoF MOS varactor RF measurement VNA coupled with interferometer,” in *Proc. 77th ARFTG Microwave Measurement Conference*, Baltimore, MD, June 2011.

List of Candidate's Works Relating to the Doctoral Thesis

Papers in Impacted Journals

[A1] M. Randus, K. Hoffmann, "A method for direct impedance measurement in microwave and millimeter-wave bands," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 8, pp. 2123–2130, 2011. ISSN 0018-9480. (contribution 50 %)

[A2] M. Randus, K. Hoffmann, "Microwave impedance measurement for nanoelectronics," *Radioengineering*, vol. 20, no. 1, pp. 276–283, 2011. ISSN 1210-2512. (contribution 50 %)

Papers Excerpted in Web of Science

[B1] M. Randus and K. Hoffmann, "A simple method for extreme impedances measurement – experimental Testing," in *Proc. 72nd ARFTG Microwave Measurement Symposium* [CD-ROM], pp. 40–44, Portland, OR, USA, 2008. ISBN 978-1-4244-2299-9. (contribution 50 %)

[B2] M. Randus and K. Hoffmann, "Design of SMA 50 Ohm Load Using 3D EM field simulator: comparison with reality," in *Proc. 14th Conference on Microwave Techniques COMITE 2008* [CD-ROM], pp. 314–316, Prague, Czech Republic, 2008. ISBN 978-1-4244-2137-4. (contribution 50 %)

Papers in Reviewed Journals

None

Patents

[C1] K. Hoffmann and M. Randus, ”Measurement system for measurement of extreme impedances of microwave circuit elements,” *Patent 302565*, Úřad průmyslového vlastnictví. 2011-06-02. (in Czech). (contribution 50 %)

[C2] K. Hoffmann and M. Randus, ”Measurement system for measurement of extreme impedance of microwave circuits elements,” *Patent 302220*, Úřad průmyslového vlastnictví. 2010-11-22. (in Czech). (contribution 50 %)

[C3] K. Hoffmann and M. Randus, ”Measurement system for measurement of extreme impedance of microwave circuits elements,” *Patent 302219*, Úřad průmyslového vlastnictví. 2010-11-22. (in Czech). (contribution 50 %)

[C4] K. Hoffmann and M. Randus, ”Measurement system for measurement of extreme impedance of microwave circuits elements,” *Patent 302218*, Úřad průmyslového vlastnictví. 2010-11-22. (in Czech). (contribution 50 %)

[C5] K. Hoffmann and M. Randus, ”Measurement system for measurement of extreme impedance of microwave circuits elements,” *Patent 302217*, Úřad průmyslového vlastnictví. 2010-11-22. (in Czech). (contribution 50 %)

[C6] K. Hoffmann and M. Randus, ”Arrangement for measurement of extreme impedances of microwave circuit elements,” *Patent 301389*, Úřad průmyslového vlastnictví. 2009-12-30. (in Czech). (contribution 50 %)

Utility Models

[D1] K. Hoffmann and M. Randus, "Measurement system for measurement of microwave circuits elements," *Užitný vzor 21163*, Úřad průmyslového vlastnictví. 2010-08-09. (in Czech). (contribution 50 %)

[D2] K. Hoffmann and M. Randus, "Measurement system for measurement of extreme impedance of microwave circuits elements," *Užitný vzor 20402*, Úřad průmyslového vlastnictví. 2010-01-04. (in Czech). (contribution 50 %)

[D3] K. Hoffmann and M. Randus, "Measurement system for measurement of extreme impedance of microwave circuits elements," *Užitný vzor 20403*, Úřad průmyslového vlastnictví. 2010-01-04. (in Czech). (contribution 50 %)

[D4] K. Hoffmann and M. Randus, "Measurement system for measurement of extreme impedance of microwave circuits elements," *Užitný vzor 20404*, Úřad průmyslového vlastnictví. 2010-01-04. (in Czech). (contribution 50 %)

[D5] K. Hoffmann and M. Randus, "Measurement system for measurement of extreme impedance of microwave circuits elements," *Užitný vzor 20405*, Úřad průmyslového vlastnictví. 2010-01-04. (in Czech). (contribution 50 %)

[D6] K. Hoffmann and M. Randus, "3dB power divider with differential outputs," *Užitný vzor 19330*, Úřad průmyslového vlastnictví. 2009-02-16. (in Czech). (contribution 50 %)

[D7] K. Hoffmann and M. Randus, "Arrangement for measurement of extreme impedances of microwave circuit elements," *Užitný vzor 18059*, Úřad průmyslového vlastnictví. 2007-11-26. (in Czech). (contribution 50 %)

Other Publications

[E1] M. Randus and K. Hoffmann, "Calculation of maximal applicable gain for the generalized and the direct method for extreme impedances measurement," in *Proc. 76th ARFTG Microwave Measurement Conference* [CD-ROM], pp. 63–68, Clearwater Beach, FL, USA, 2010. ISBN 978-1-4244-7448-6. (contribution 50 %)

[E2] M. Randus and K. Hoffmann, "A novel method for direct impedance measurement in microwave and mm-wave bands," in *Proc. 75th ARFTG Microwave Measurement Conference* [CD-ROM], pp. 83–87, Anaheim, CA, USA, 2010. ISBN 978-1-4244-6365-7. (contribution 50 %)

[E3] M. Randus and K. Hoffmann, "Generalized method for broadband measurement of extreme impedances," in *Proc. 74th ARFTG Microwave Measurement Conference* [CD-ROM], pp. 76–79, Broomfield, CO, USA, 2009. ISBN 978-1-4244-5713-7. (contribution 50 %)

[E4] M. Randus and K. Hoffmann, "A simple method for extreme impedances measurement," in *Proc. 70th ARFTG Microwave Measurement Conference* [CD-ROM], pp. 46–50, Tempe, AZ, USA, 2007. (contribution 50 %)

[E5] M. Randus and K. Hoffmann, "Measurement of extreme impedances," in *Proc. 15th Conference on Microwave Techniques COMITE 2010*, pp. 95–98, Brno, Czech Republic, 2010. ISBN 978-1-4244-6351-0. (contribution 50 %)

[E6] M. Randus, "Generalized method for extreme impedances measurement," in *Sborník semináře o řešení doktorského projektu Grantové agentury České republiky č. 102/08/H027 v roce 2009 – Pokročilé metody, struktury a komponenty elektronické bezdrátové komunikace*, pp. 127–130, Brno, Czech Republic, 2009. ISBN 978-80-214-4017-3. (in Czech) (contribution 100 %)

[E7] M. Randus, "Measurement of extreme impedances," in *Scientific Seminars - Proceedings from year 2008/2009 Volume VIII. Part of GACR Project 102/08/H018.*, pp. 30–35, Prague, Czech Republic, 2009. ISBN 80-86582-23-X. (contribution 100 %)

[E8] M. Randus, "Metoda pro měření vysoce odrazivých zátěží," in *Sborník příspěvků konference Zvůle 2008*, pp. 228–231, Zvůle, Czech Republic, 2008. ISBN 978-80-214-3709-8. (in Czech) (contribution 100 %)

List of Other Candidate's Works

Papers Excerpted in Web of Science

[F1] P. Hudec, J. Raboch, M. Randus, K. Hoffmann, A. Holub, M. Švanda and M. Polívka, "Microwave radar sensors for active defense systems," in *Proc. European Radar Conference 2009*, pp. 581–584, Rome, Italy, 2009. ISBN 978-1-4244-4748-0. (contribution 14 %)

[F2] P. Hudec, K. Hoffmann, M. Randus, M. Ryneš, J. Raboch, M. Švanda and M. Polívka, "Radar sensor for detection of anti-armour missiles," in *Proc. European Radar Conference 2008*, pp. 116–119, Amsterdam, Netherlands, 2008. ISBN 978-1-4244-3794-8. (contribution 14 %)

[F3] M. Randus and K. Hoffmann, "Broadband medium-power transistor amplifier 12–18 GHz," in *Proc. 17th International Conference Radioelektronika 2007*, pp. 307–311, Brno, Czech Republic, 2007. ISBN 978-1-4244-0821-4. (contribution 50 %)

Papers in Impacted Journals, Papers in Reviewed Journals, Patents, Utility Models

None

Other Publications

[G1] M. Randus, P. Hudec and K. Hoffmann, "Short-range detection and measurement of small high-speed objects in microwave frequency region," in *Proc. 70th ARFTG Microwave Measurement Conference* [CD-ROM], pp. 66–69, Tempe, AZ, USA, 2007. (contribution 33 %)

[G2] P. Hudec, M. Randus, J. Raboch and K. Hoffmann, "Radar sensor for detection and measurement of anti-armour missiles," in *Proc. 18th International Travelling Summer School on Microwaves and Lightwaves*, pp. 299–313, Prague, Czech Republic, 2008. (contribution 25 %)

Response and Reviews

Citations

Paper [E4] was cited in:

A. Lewandowski, D. LeGolvan, R. A. Ginley, T. M. Wallis, A. Imtiaz, and P. Kabos, "Wideband measurement of extreme impedances with a multistate reflectometer," in *Proc. 72nd ARFTG Microwave Measurement Symposium*, pp. 45–49, Portland, OR, 2008. ISBN 978-1-4244-2300-2.

Papers [B1] and [E4] were cited in:

T. M. Wallis, A. Imtiaz, S.-H. Lim, P. Kabos, K. Kim, P. Rice, and D. Filipovic, "Broadband measurements of nanofiber devices: Repeatability and random error analysis," in *Proc. 76th ARFTG Microwave Measurement Symposium*, pp. 1–6, Clearwater Beach, FL, USA, 2010. ISBN 978-1-4244-7448-6.

Paper [B2] was cited in:

Wei Chen Lee and Hill Wu, "Computer-aided analysis and measurement of an interconnection system," *Advanced Materials Research*, vol. 308–310, pp. 2279–2285, 2011.

Paper [B1] was cited in:

A. El Fellahi, D. Glay, K. Haddadi and T. Lasri, "High impedance RF four-port reflectometer," in *Proc. 41st European Microwave Conference*, pp. 491–494, Manchester, UK, 2011. ISBN 978-1-61284-235-6.

Awards

April 2010 – Paper [E5] was awarded:

„Students' Best Paper Award"
Microwave and Radio Electronics Week 2010 – COMITE 2010, Brno, Czech Republic

December 2009 – Paper [E3] was awarded:

„Best Interactive Forum Presentation Award"
74th ARFTG Microwave Measurements Conference, Broomfield, CO, USA

December 2008 – Paper [B1] was awarded:

„Best Interactive Forum Presentation Award"
72nd ARFTG Microwave Measurements Symposium, Portland, OR, USA

November 2007 – Paper [E4] was awarded:

„Best Conference Oral Presentation Award"
70th ARFTG Microwave Measurements Conference, Tempe, AZ, USA

April 2007 – Paper [F3] was awarded:

„Students' Best Paper Award"
17th International Conference Radioelektronika 2007, Brno, Czech Republic

Summary

Emerging novel microwave devices based on nanostructures, especially carbon nanotubes, showed an urgent need for broadband measurement of extreme impedances – impedances that are substantially greater or lower than a 50 Ω reference impedance of a measurement system. The typical input impedance of carbon nanotube devices is usually in orders of tens and hundreds of kΩ. However, the classical method for impedance measurement based on measuring a reflection coefficient of a device under test (DUT) by a vector network analyzer (VNA) suffers from serious inaccuracy problems for very high and very low impedances due to low reflection coefficient sensitivity.

A novel method for measurement of extreme input impedances was developed. The method is addressed as nearly balanced bridge method and it is based on adding or subtracting of a reference reflection coefficient from the reflection coefficient of the DUT by a passive four-port network, amplifying the difference and measuring the resulting signal as a transmission coefficient by a common VNA. By this means effect of errors of the VNA (including drift, cable stability, noise) can be significantly reduced. The method was completely mathematically described and successfully experimentally verified. Comparison of the obtained results with the classical method of reflection coefficient measurement by a VNA clearly proved that the proposed measurement method significantly improves measurement system stability and can be used for measurement of extreme impedances.

Another novel method, which is partially based on the principles of the preceding method, was developed. The method is based on simultaneous subtracting of a reference reflection coefficient from the reflection coefficient of the DUT in one arm of the measurement system and adding of the reference reflection coefficient to the reflection coefficient of the DUT in the second arm of the measurement system. The addition and subtraction is done by a pair of 90-degree or 180-degree, 3 dB hybrid couplers. Signals proportional to the difference and to the sum of the two reflection coefficients are amplified by amplifiers and their ratio is measured by a common VNA. The result of this ratioed measurement is in ideal case directly proportional to a value of the input impedance or admittance of the DUT depending on the reference impedance and the active source port of the VNA. Therefore, the method is addressed as the method for direct impedance measurement. The method was successfully experimentally verified and the results were compared with the classical method of reflection coefficient measurement by a VNA, that clearly proved improved performace of the proposed method.

Résumé

Nové mikrovlnné komponenty založené na nanostrukturách, především na uhlíkových nanotrubicích, ukazují potřebu širokopásmového měření extrémních impedancí – vstupních impedancí, které jsou výrazně menší nebo výrazně větší než je 50Ω referenční impedance měřicího systému. Typická vstupní impedance prvků založených na uhlíkových nanotrubicích se většinou pohybuje v řádu desítek a stovek kΩ. Klasická metoda mikrovlnného měření impedance využívající měření koeficientu odrazu pomocí vektorového analyzátoru obvodů (VNA) a následný výpočet impedance je pro velmi velké a velmi malé impedance zatížena značnou chybou způsobenou malou citlivostí koeficientu odrazu.

Byla proto vyvinuta nová metoda pro měření extrémních impedancí. Metoda je označena jako metoda téměř vyváženého můstku a je založena na přičítání nebo odčítání referenčního koeficientu odrazu od koeficientu odrazu měřeného zařízení (DUT) pomocí pasivního čtyřbranu, zesílení rozdílu a měření výsledného signálu jako koeficientu přenosu pomocí běžného VNA. Tímto způsobem lze výrazně potlačit vliv chyb VNA včetně driftu, omezené stability kabelů a šumu. Tato metoda byla kompletně matematicky popsána a úspěšně experimentálně ověřena. Získané výsledky byly porovnány s klasickou metodou měření koeficientu odrazu pomocí VNA a potvrdily, že předkládaná měřicí metoda výrazně zlepšuje stabilitu měřicího systému, a lze ji použít k měření extrémních impedancí.

Dále byla vyvinuta druhá měřicí metoda, která částečně vychází z principů předchozí metody. Metoda je založena na současném odčítání referenčního koeficientu odrazu od koeficientu odrazu DUT v jedné větvi měřicího systému a přičítání referenčního koeficientu odrazu ke koeficientu odrazu DUT ve druhé větvi měřicího systému. Sčítání a odčítání je provedeno pomocí dvojice 90stupňových nebo 180stupňových 3dB hybridních členů. Signály úměrné rozdílu a součtu těchto dvou koeficientů odrazu jsou zesíleny zesilovači a jejich vzájemný poměr je změřen běžným VNA. Protože výsledek tohoto poměrového měření je v ideálním případě přímo úměrný hodnotě měřené vstupní impedance nebo admitance DUT v závislosti na použité referenční impedanci a aktivním vstupu VNA, je metoda označena jako metoda pro přímé měření impedance. Metoda byla úspěšně experimentálně ověřena a výsledky byly porovnány s klasickou metodou měření koeficientu odrazu pomocí VNA, což jsně prokázalo zlepšenou přesnost měření u předkládané metody.