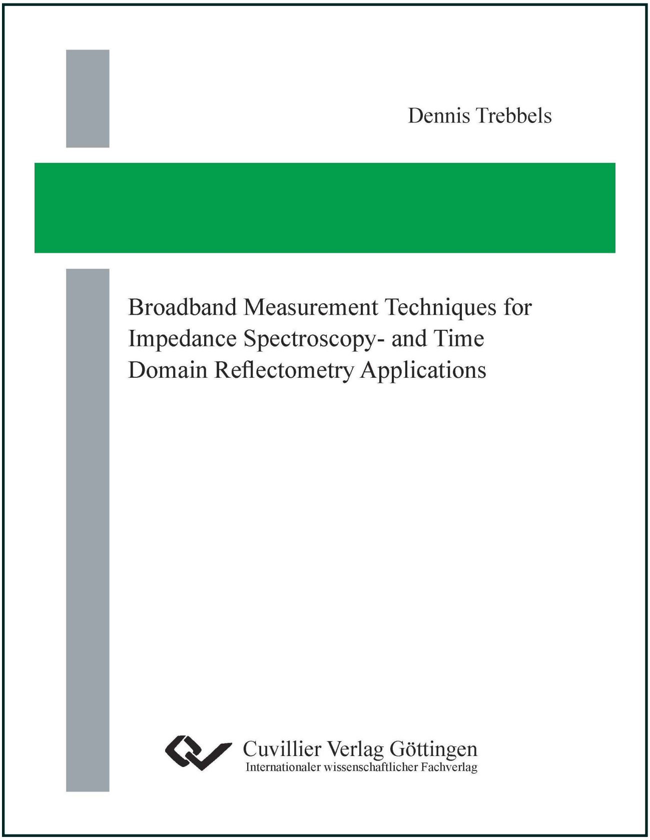
Dennis Trebbels (Autor)

Broadband Measurement Techniques for Impedance Spectroscopy- and Time Domain Reflectometry Applications



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1 Introduction

Broadband electrical impedance measurement, often referred to as impedance spectroscopy (IS), is a well known method for characterizing the electric and dielectric properties of a material under test (MUT). This method applies an alternating voltage signal or current signal via electrodes to the MUT and monitors the system response which is the resulting current through the MUT or the developed voltage across the MUT. The frequency of the excitation signal is varied within a defined frequency window. The response of the MUT is typically a complex function which results in a characteristic amplitude and phase shift of the flowing current with respect to the signal voltage. An application specific analysis and interpretation of the measured complex impedance transfer function can give valuable information about the state of the MUT. Often model based analysis methods are found which usually try to explain and describe the transfer function by physical properties of the MUT and associated additional side effects caused e.g. by measurement electrode polarization, stray capacitances or long measurement cables.

Impedance spectroscopy is used in almost all scientific and technical fields within a frequency range from below 1 Hz up to several ten GHz. Applications include battery and fuel cell analysis [1], analysis of organic and inorganic chemical substances [2, 3] and electrochemical systems [4, 5], characterization of electrical machines, drives and transformers [6–9], microfluidic applications [10, 11], soil moisture measurement [12–16], flow sensors [17, 18], infrastructure and construction monitoring [19, 20], characterization of organic and inorganic semiconductors [21], readout of piezo sensors [22], biological tissue analysis [23, 24] food and drug analysis and quality monitoring [25], biosensors [26] and moisture measurement of granular materials [27]. The given list is not complete but shows that impedance spectroscopy is a powerful tool in many applications.

A more detailed analysis of the above listed applications shows, that each application has specific requirements for the impedance measurement. Measurement parameters such as the bandwidth of the excited measurement signal, measurement signal amplitude and signal duration must be adjusted to fulfil the specific needs. For applying the measurement signal to the MUT and for recording the system response it is usually required to either attach electrodes to the MUT or installing the MUT inside a defined test cell such as e.g. a parallel plate capacitor. Depending on the properties of the MUT and the used measurement setup measurement errors will occur and must be taken into account. The following sections within the first chapter describe the physical basics of broadband impedance measurement, impedance spectra representation, different types of measurement signals, suitable measurement equipment and typical electrode configurations. Last but not least an overview about current activities and advances in electronic measurement equipment dedicated for impedance spectroscopy is presented. Although several interesting measurement concepts have been introduced within the last decades, there is still a lack of simple, small and efficient electronic measurement solutions which could be used in a real product outside the laboratory.

1.1 Impedance Basics

Most materials can be characterized by analysing their frequency dependent electric and dielectric properties. The measured values are a function of the sample geometry and the individual characteristic material properties. In the field of impedance spectroscopy there are two effects which are measured and analysed when a voltage signal is applied to a sample and a current flows through the sample. The first effect are losses in the material which always occur when a current is flowing. The second effect is the capability of the material to store energy. Usually the losses are described by a material specific characteristic conductivity which results in an effective conductance for a given geometry. The capability of storing energy is usually described by the (relative) permittivity of the material. Each material has a characteristic permittivity which leads to a measured capacitance when a sample of a defined geometry is placed between electrodes such as e.g. a parallel plate capacitor. Figure 1.1 A illustrates an often found model for a material placed between two parallel plates which serve as electrodes. The size A of the electrodes

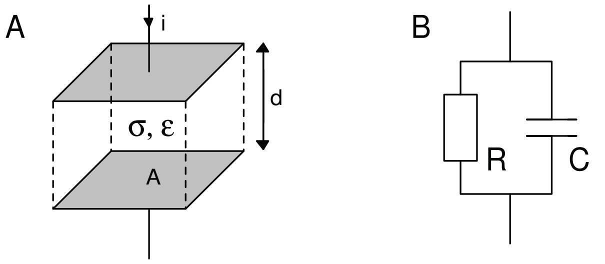

Figure 1.1: A: Model of a typically used test cell geometry for measuring material specific properties such as conductivity σ and permittivity ε. B: Equivalent electrical schematic describing the test cell with a lossy material between the electrodes.

$$G = \frac{\sigma * A}{d} \tag{1.1}$$

$$C = \frac{\varepsilon_0 * \varepsilon_r * A}{d} \tag{1.2}$$

$$R = \frac{1}{G} \tag{1.3}$$

In the scientific literature it is common to express the two material properties "conductivity" and "permittivity" by either a complex conductivity $\underline{\sigma}$ or by a complex permittivity $\underline{\varepsilon}$. The definition for complex conductivity is given by equation 1.4 and the definition for complex permittivity is given by 1.5. If the complex conductivity is used the real part represents the losses in the material and the imaginary part represents all energy storage effects. If the complex permittivity is used the real part represents all energy storage effects and the imaginary part represents all losses in the material. Both notations can be used to express complex material properties. The relationship between the complex conductivity and the complex permittivity is given by equation 1.6 [3].

$$\underline{\sigma} = \sigma' + j\sigma'' \tag{1.4}$$

$$\underline{\varepsilon_r} = \varepsilon_r' + j\varepsilon_r'' \tag{1.5}$$

$$\underline{\sigma} = j\omega\varepsilon_0\underline{\varepsilon_r} \tag{1.6}$$

The resulting relationship between the four variables is given by equations 1.7 and 1.8. A comprehensive derivation of the presented equations can be found in [3].

$$\sigma'' = \omega\varepsilon_0\varepsilon_r' \tag{1.7}$$

$$\varepsilon_0\varepsilon_r'' = \frac{\sigma'}{\omega} \tag{1.8}$$

If a sinusoidal voltage U is applied to the electrodes (equation 1.9) a sinusoidal current I (equation 1.10) will flow through the material. The ratio between the voltage signal amplitude and the resulting current signal amplitude is expressed by the complex impedance $\underline{Z}$ (equation 1.11). Figure 1.2 A illustrates typical sinusoidal voltage and current signals which can be measured over a complex load with a characteristic frequency dependent impedance Z_0 and phase shift $\varPhi$.

$$U = U_0 e^{j(\omega t + \varphi_u)} \tag{1.9}$$

$$I = I_0 e^{j(\omega t + \varphi_i)} \tag{1.10}$$

$$\underline{Z} = \frac{U}{I} = \frac{U_0 e^{j(\omega t + \varphi_u)}}{I_0 e^{j(\omega t + \varphi_i)}} = \frac{U_0}{I_0} * e^{j(\varphi_u - \varphi_i)} = Z_0 e^{j\phi} \tag{1.11}$$

In the field of electrical engineering it is common to express the complex impedance $\underline{Z}$ in terms of a real part R and an imaginary part X (equation 1.12). The imaginary part X is called reactance. Figure 1.2 B shows an often used graphical representation of the complex impedance as a pointer. The length $|\underline{Z}|$of the pointer is given by equation 1.13 and the angle $\varPhi$ is given by equation 1.14. Vice versa the real part R and the imaginary part X can be calculated out of a measured amplitude ratio and a measured phase shift by equations 1.15 and 1.16.

$$\underline{Z} = |\underline{Z}|\, e^{j\varPhi} = Z' + jZ'' = R + jX \tag{1.12}$$

$$|\underline{Z}| = \sqrt{R^2 + X^2} \tag{1.13}$$

$$\varPhi = arctan(\frac{X}{R}) = arctan(\frac{Z''}{Z'}) \tag{1.14}$$

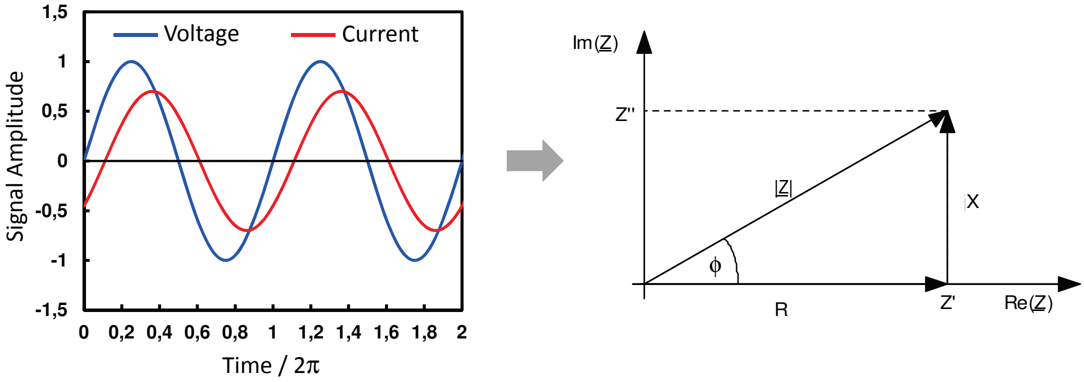

Figure 1.2: Left side: Typical sinusoidal voltage and current signal for a randomly selected complex impedance. A frequency dependent amplitude ratio and phase shift can be observed when varying the frequency. Right side: Representation of the complex impedance in the complex plane as commonly used in the field of electronics. The complex impedance consists of a real part and an imaginary part.

The frequency dependent electric behaviour of the equivalent circuit presented in figure 1.1 B can be calculated by the parallel connection of the capacitor C and the resistor R. For parallel combinations it is often easier to express the overall electric behaviour by the complex admittance $\underline{Y}$ which is the inverse of the complex impedance $\underline{Z}$. Equation 1.17 derives the admittance and equation 1.18 derives the impedance of the equivalent circuit.

$$\underline{Y} = G + j\omega C = \frac{A}{d}(\sigma + j\omega C\varepsilon_0\varepsilon_r) \tag{1.17}$$

$$\underline{Z} = Z' + jZ'' = \frac{1}{\underline{Y}} = R + jX = \frac{G - j\omega C}{G^2 + (\omega C)^2} \tag{1.18}$$

1.2 Impedance Spectra Representation

The measured impedance is a function of the frequency. Thus a plot of the frequency dependent impedance values of a MUT is often referred to as "impedance spectrum". There are several ways for graphically presenting the complex impedance data. In the field of impedance spectroscopy there are typically two types of diagrams found: the Bode Diagram and the Nyquist Diagram. The Bode Diagram of the equivalent electrical schematic is shown in figure 1.3 (left side). There are two plots in the Bode Diagram, one plot shows the modulus and the second plot shows the phase. Modulus and phase can be calculated by equations 1.13 and equation 1.14 when the real part Re($\underline{Z}$) and the imaginary part Im($\underline{Z}$) are known. For the equivalent circuit in figure 1.1 B the real and imaginary parts are given by equations 1.19 and 1.20. Advantage of this representation is the fact that both plots are functions of the frequency and it is intuitive to discover interesting frequency dependent areas within a measured broad frequency

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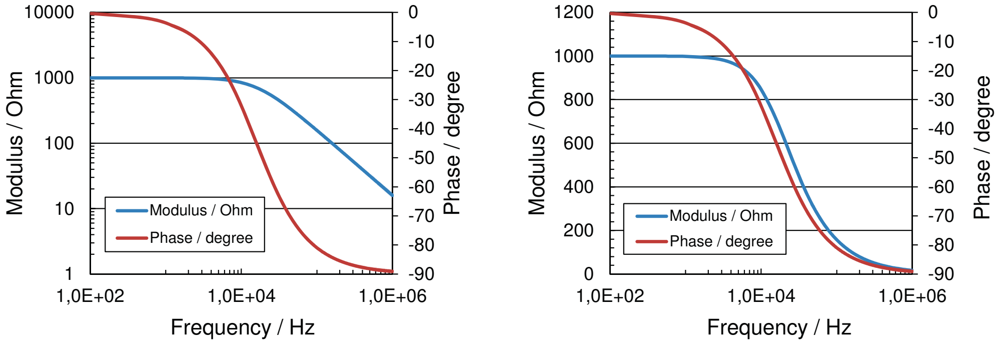

Figure 1.3: Left side: Bode Diagram of a lossy dielectric. Magnitude and phase are plotted against the frequency. Magnitude and frequency axes are logarithmic. Right side: Modified Bode Diagram with linear magnitude axis as sometimes used within this thesis.

$$Re(\underline{Z}) = \frac{\frac{1}{R}}{(\frac{1}{R})^2 + (\omega C)^2} \tag{1.19}$$

$$Im(\underline{Z}) = \frac{-\omega C}{(\frac{1}{R})^2 + (\omega C)^2} \tag{1.20}$$

As an alternative to the Bode Diagram a Nyquist Diagram can be used. In this case the imaginary part Im($\underline{Z}$) of the impedance is plotted against the real part Re($\underline{Z}$) of the impedance as shown in figure 1.4. The characteristic curve of the equivalent schematic shown in figure 1.1 B is a semicircle. Drawback of this representation is the fact that there is no intuitive link to the frequency which belongs to each pair of real and imaginary components. Advantage is that it is possible to obtain the impedance values at a frequency of zero and at infinite frequency by extrapolation of the data practically measured within a limited frequency range. In addition it is relatively easy to discover even small changes in the complex impedance at very low or at very high frequencies. This type (

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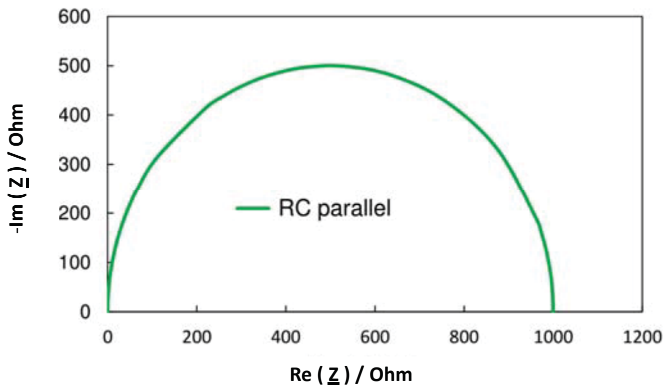

Figure 1.4: Nyquist Diagram of a lossy dielectric. Real part and imaginary part are plotted against each other. Each point of the curve belongs to a defined frequency.

1.3 Broadband Measurement Signals

Goal of the broadband impedance measurement is to derive the frequency dependent complex transfer function of the unknown system formed by the electrodes and the attached test sample. Therefore it is required to apply stimulus signals (e.g. voltage signals or current signals) which contain multiple frequency components inside the band of interest. There are two options for applying multiple frequencies to the unknown MUT: sweeping the signal within a defined frequency range which means hopping from one frequency to the next frequency or alternatively applying a broadband signal which contains multiple frequencies at a time. Sweeping the measurement signal is often referred to as measuring in the "Frequency Domain" and applying a signal which contains multiple frequencies at a time is usually referred to as measuring in the "Time Domain". The following section describes typical signals which are often found in impedance measurement systems. Each signal has its inherent advantages and disadvantages. The choice of the best stimulus signal for a given application depends on several individual boundary parameters such as measurement time, required signal to noise ratio (SNR), achievable bandwidth and last but not least efficient and robust signal processing of the captured raw data.

One of the best known and frequently found measurement signals is the pure sine wave signal. A sinusoidal excitation voltage or current is applied to the MUT. If a passive MUT is measured within a linear range the resulting response signal (either a current or voltage signal) is a sinusoidal signal as well. Both signals can be captured and it is a straight forward way to compute the complex impedance as shown in equations 1.12 to 1.16. After measuring the impedance at one specific frequency it is switched to the next frequency and the measurement cycle is repeated. Great advantage of this method is the high SNR which can be achieved with this method because the whole signal energy is concentrated at a single frequency. Figure 1.5 shows a sine wave signal in time domain (left diagram) and in the frequency domain (right diagram). In addition it is relatively easy to generate a sinusoidal excitation signal and there are lots of analog and digital circuits and signal processing methods for processing sine wave signals with high accuracy. However - drawback of a sine wave sweep is the long measurement time which is required when sweeping over several decades of frequency. It is often not possible to measure for such a long time e.g. when fast applications such as single cell sorting in microfluidic systems have to be processed in real-time. In addition there are systems where the MUT varies with time such as e.g. a heart muscle which is continuously moving. In this thesis the sine wave signal is used for measuring the phase shift with very high accuracy and resolution in a slow medical system. The target application is hematocrit measurement in closed loop blood circulation systems found in dialysis machines. An electronic circuit is developed which can precisely measure within a frequency range of a few Hz up to several MHz.

An often used alternative to a pure sine wave signal is a so called multisine signal. Such a signal consists of multiple sinusoidal signals which are superposed to each other and applied at the same time to the MUT. Figure 1.6 shows such a multisine signal in the time domain (left diagram) and in the frequency domain (right diagram) which consists of five discrete sine wave signals. On the first view it looks attractive to use such a signal since it is straight forward to understand. But there are several drawbacks which often limit the usability within real applications. Major concern is the fact that superposing multiple sinusoidal signals often leads to very high excitation signal amplitudes. Such high amplitudes are difficult to generate and in many cases the MUT does not behave linear when large signal amplitudes are applied. There are several interesting methods

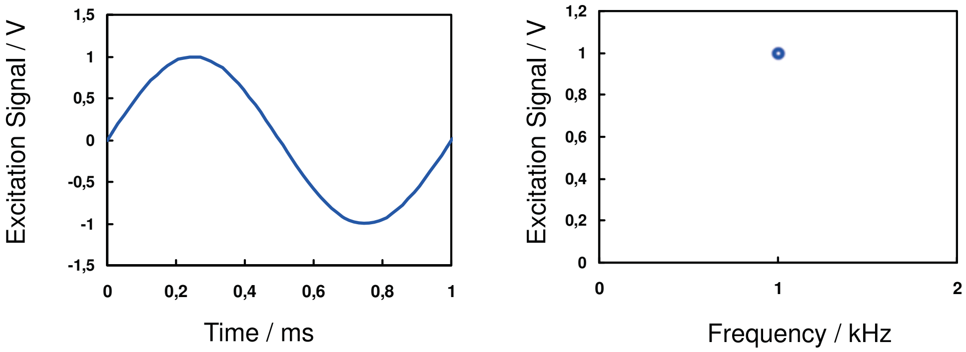

Figure 1.5: Plot of a pure sine wave signal in time domain (left) and frequency domain (right). The whole signal energy is concentrated at one discrete frequency and allows for measuring with an excellent SNR.

and approaches which show how to carefully select the frequencies and which phasing relative to the other frequencies should be used in order to obtain a low overall amplitude of the resulting sum signal [28–31]. These methods work quite well for a low number of frequencies but the problem of optimization becomes very difficult for a larger number of frequencies. A further drawback of the multisine signal is that it is not so easy to generate. If an analog circuit should be used for signal generation then for each frequency component one signal source is required which results in a large overall circuit when a
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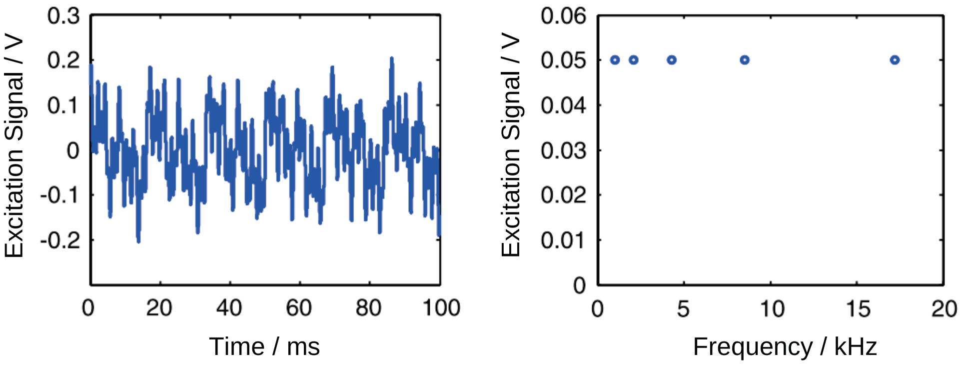

Figure 1.6: Graphical presentation of a multisine signal composed of five discrete sinusoidal signals. The total signal energy is distributed over the five contained discrete frequencies [25].

Another very interesting type of excitation signals with attractive properties is a so called chirp signal. A chirp signal usually is a sinusoidal excitation signal which continuously varies its frequency according to some kind of "ramping function". The most common type of a chirp signal is a linear chirp C(t) which can be expressed by equation 1.21 where A denotes the amplitude, f_0 denotes the initial and f_{fin} denotes the final frequency of the chirp signal and T_{ch} denotes the duration of the chirp signal.

$$C(t) = Asin(2\pi(f_0 t + (f_{fin} - f_0)t^2/2T_{ch}) \qquad (1.21)$$

Equation 1.21 shows one of the advantages that a chirp signal has compared to many other broadband signals: its excellent scalability. The parameters f_0 and f_{fin} determine the bandwidth $B = f_{fin} - f_0$ and can be chosen independent from each other and independent from the remaining parameters such as amplitude and duration. The chirp signal properties can therefore easily be adjusted to the individual requirements given by each application. Figure 1.7 shows a linear chirp signal with a duration of 20 ms and a bandwidth up to 8 kHz. The amplitude spectrum on the right side shows a further advantage of the chirp signal compared to many other signals. The amplitude spectrum is flat which allows for measuring the impedance of the MUT at all covered frequencies with an acceptable SNR. Drawback of the chirp signal is that it is required to have an appropriate high sampling rate for generating the excitation signal and for capturing the response signal. The energy of the chirp signal is spread over the entire bandwidth which of course leads to a lower SNR for each discrete impedance value computed out of the sampled raw data. A detailed overview over chirp signals, modified chirp signals and correspo

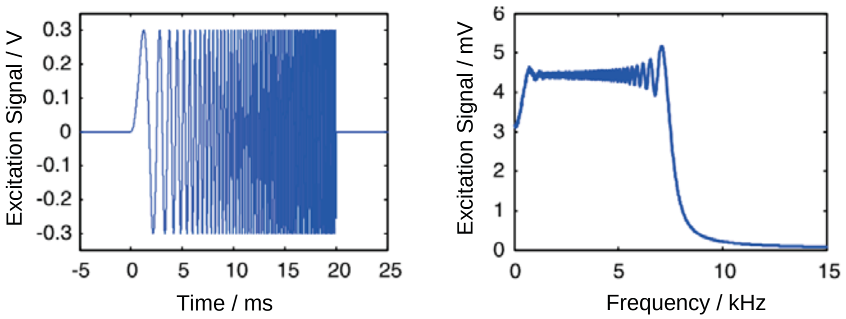

Figure 1.7: Graphical presentation of a linear chirp signal with a duration of 20 ms covering a bandwidth of several kHz. The flat amplitude spectrum shown on the right side allows for measuring at all covered frequencies with an acceptable SNR [25].

Besides sinusoidal signals there are often pulsed signals found in impedance measurement systems. The simplest broadband signal which can be generated is a step pulse signal or a square wave signal as shown in figure 1.8. Such a signal is simple to understand and there are many known and straight forward to implement signal processing methods available. Major drawback of such a pulsed signal is the low amplitude of the higher frequency components which follows a $\frac{sin(x)}{x}$ envelope. For broadband impedance measurement systems which cover a few decades of frequencies this often means a poor SNR for the higher frequency measurement results. However - there are several interesting ways to use the properties of a square wave signal in combination with special "electrodes" e.g. in die field of Time Domain Reflectometry (TDR). Furthermore in some applications it is possible to fit the sampled response signal to a known model of the MUT and achieve a quite good overall measurement result.

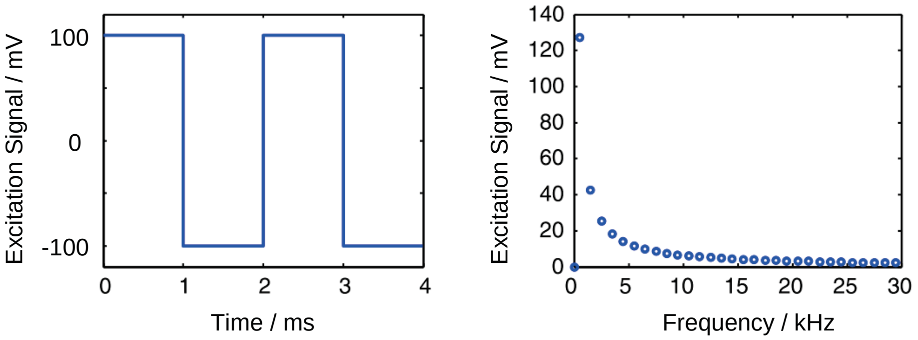

Figure 1.8: Graphical presentation of a square wave signal and its amplitude spectrum. The square wave signal is easy to generate but the decaying amplitude of higher frequency components is a problem in many applications which require a certain SNR [25].

A frequently found and smart method for improving the SNR at higher frequencies is to replace the standard square wave signal by a defined pulse train which follows certain mathematical boundary conditions. The probably best known method is based on so called "Maximum Length Sequence" (MLS) signals. Figure 1.9 shows such a MLS signal and the corresponding amplitude spectrum. On one hand it can be said that the spectrum is not as flat and ideal as it is in the case of a chirp signal. On the other hand the spectrum shows improved signal energy in the higher frequency ranges compared to a standard pulse. A MLS sequence is very easy to generate and processing of the sampl uch as the " ls and relate

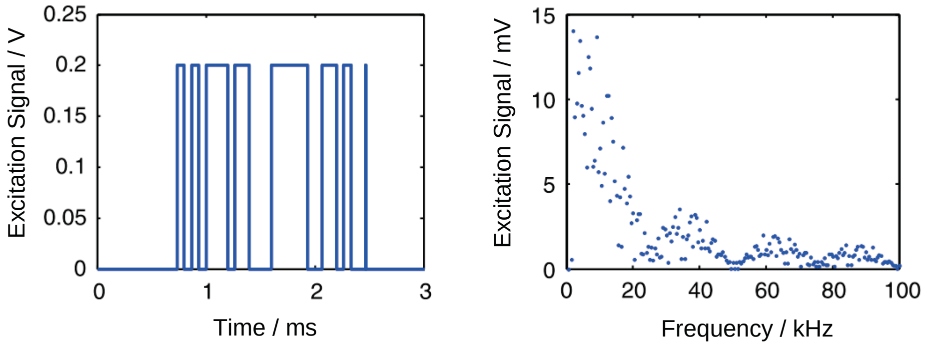

Figure 1.9: Graphical presentation of a Maximum Length Sequence (MLS). The MLS pulse train follows certain mathematical boundary conditions. The resulting amplitude spectrum allows for measuring impedances even at higher frequencies with an improved SNR compared to a simple square wave signal [25].

1.4 Laboratory Measurement Equipment

Usually the target application of interest is investigated and analysed in the laboratory first. Goal of the laboratory measurements is to find interesting characteristic areas within the impedance spectrum which can be analysed according to the applications specific requirements. Here the key component of each measurement setup is a precision laboratory impedance measurement device. There are several manufacturers which offer a broad range of measurement devices optimized for the field of impedance spectroscopy. However, in many cases it is not required to use such (expensive) special equipment if an electronic laboratory is available . There are a few typical devices which are widely found in electronic laboratories and which are ideally suited for first experimental measurements.

One precision type of laboratory impedance measurement devices are so called "LCR-Meters" with programmable measurement frequency. Many devices allow to switch the measurement frequency from a few Hz up to a few MHz. For example this frequency range is ideal for most biological applications. LCR-Meters typically achieve high precision measurement results due to the fact that they operate based on pure sinusoidal excitation signals where the signal energy is concentrated at the selected measurement frequency. Drawback is the long acquisition time which limits the system to be used for static MUTs only. Figure 1.10 A shows one state-of-the-art LCR meter (Agilent E4980A) which is widely used for impedance spectroscopy applications.

Another well known type of impedance measurement devices is a network analyser. Usually they offer a wider bandwidth than LCR-meters and can measure up to a frequency range of several GHz. However - many devices cannot measure in the low frequency range of a few Hz or a few hundred Hz. Figure 1.10 B shows one modern network analyser (Agilent E5061B) which covers an exceptionally wide frequency range from 5 H
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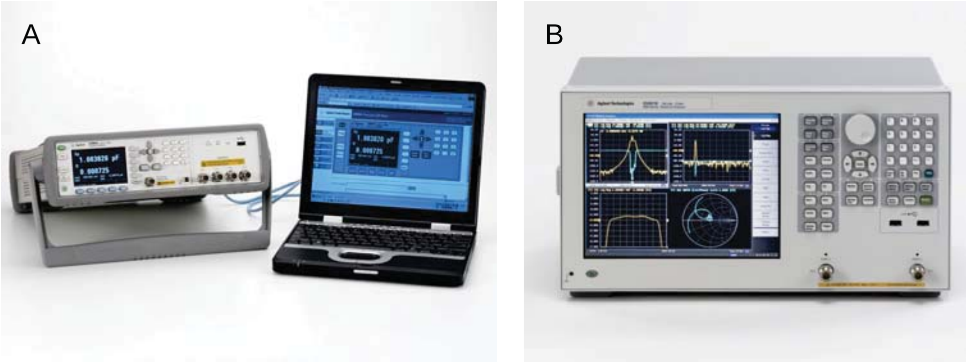

Figure 1.10: State-of-the-Art Laboratory Measurement Equipment for broadband impedance measurement. Figure A shows a precision LCR-Meter for covering a frequency range from 20 Hz to 2 MHz. Figure B shows a modern network analyser covering a frequency range from 5 Hz to 3 GHz. (Reproduced with Permission, Courtesy of Agilent Technologies, Inc.)

1.5 Electrode Configurations and Interfacing

One of the most challenging tasks in the field of Impedance Spectroscopy is to interface the MUT to the electronic measurement device or circuit. On one hand the interface should be as simple as possible, on the other hand the interface and its properties should not interact with the MUT and the measurement procedure. One common method is to directly contact the MUT with a set of at least two electrodes. Usually the electrodes are made out of metal or an alternative conductor or semiconductor. Figure 1.11 A shows such a two-electrode circuit. A current source injects a defined alternating current with adjustable frequency into the MUT. The resulting voltage drop across the MUT which arises from the current flowing through the MUT is measured between the electrodes. In some applications this setup works well, but major drawback is the measurement error caused by a potentially unknown transfer impedance between the surface of the electrode and the surface of the MUT. Especially at low frequencies electrode polarisation may cause significant measurement errors [52–55]. One well known method for compensating for such effects is to use a four-electrode configuration as illustrated in Figure 1.11 B. Here the current is injected via two electrodes similar to the two-electrode configuration. However, the resulting voltage drop across the MUT is measured with separate electrodes which are connected to a high impedance voltage measurement circuit. Any unknown transfer impedance between the electrode surface and the MUT is in series with the very high input impedance of the measurement device and therefore plays no significant role. Drawback of the four-electrode interface is the fact that it might be difficult to attach 4 electrodes with a defined geometry on the surface of the MUT. Especially when the MUT is very small (e.g. single cell analysis) this is a practical limitation.

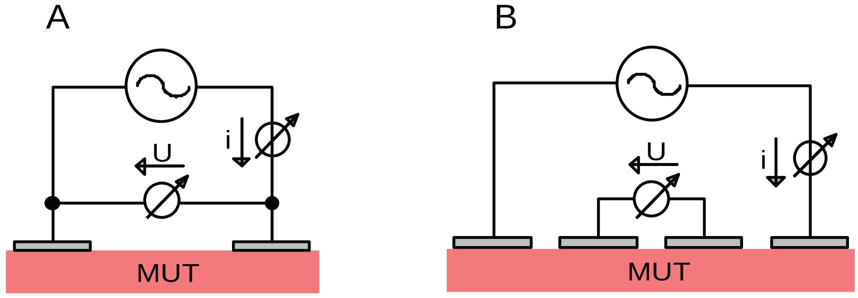

Figure 1.11: One of the best known and widely found methods for interfacing a MUT to a measurement device is to directly attach electrodes. Usually either a two-electrode configuration (A) or a four-electrode configuration (B) is used. The four-electrode interface eliminates major measurement errors caused by a unknown or unstable transfer impedance between the electrode surface and the MUT.

When the losses in the MUT are relatively small and the capability of storing energy is relatively high a capacitive measurement approach is often used. The simplest method is to build a parallel plate capacitor with a well known geometry. The MUT is installed between the plates and has direct contact to the plates as illustrated in Figure 1.12 A. If the MUT is a granular material or a liquid a coaxial test cell setup is often preferred. Here the MUT can flow inside the test cell and there is almost no unknown fringing field. Figure 1.12 B illustrates such a setup. Several industrial and automotive applications such as oil quality monitoring sensors are based on coaxial test cells.

When it is not possible to install the MUT inside a capacitive test cell and when it is difficult to attach electrodes to the MUT (e.g. due to restricted space) sometimes an

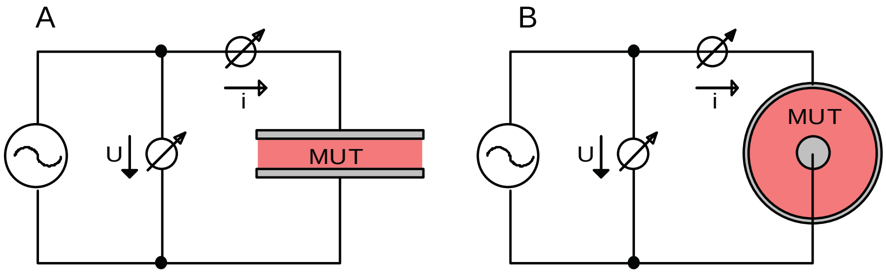

Figure 1.12: Measurement of electric and dielectric parameters of a material under test using a capacitive test cell. Often the geometry of the cell is either a parallel plate capacitor (A) or a coaxial capacitor (B).

open ended coaxial line is used. Especially when high frequency signals up to several GHz are of interest this type of probe is often found. The measurement signal is fed into a coaxial line which ends at the surface of the MUT. The injected measurement signal travels along the line until it reaches the open end. Here a reflection occurs and the reflected signal is travelling back to the measurement device. The reflection coefficient depends on the properties of the MUT which forms a complex electrical load. In most cases the end of the line has a special geometry in order to redirect the fringing field which occurs at the end of the line. The fringing field penetrates the MUT and is influenced by its electric and dielectric properties. Figure 1.13 illustrates such a setup.

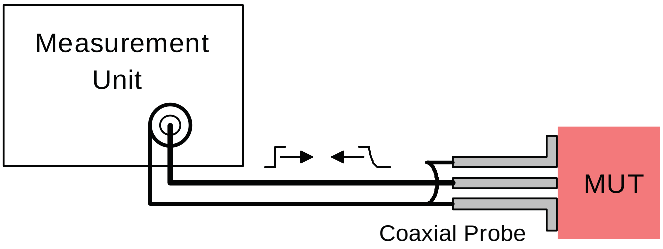

Figure 1.13: Measurement of electric and dielectric parameters of a MUT using an open ended coaxial probe. The probe end is attached to the surface of the MUT. This type of interface is often used when the space is restricted and when high frequency signals up to several GHz are of interest.

A similar approach to the open ended coaxial line is to embed a suitable sensor line into the MUT as illustrated in Figure 1.14. In applications such as e.g. soil moisture measurement it is common to use flat ribbon cables as sensor lines. Flat ribbon cables have a large fringing field which penetrates the surrounding media. The electric and dielectric properties of the media influence the characteristic wave impedance of the embedded transmission line. Any injected broadband measurement signal is distorted in a characteristic way while travelling along the line. The distorted signal is captured by the measurement electronics and analysed. In many practical applications a step pulse with sharp rising edges is used as a broadband measurement signal. The injected pulse is travelling along the line until it reaches the open end of the line. Here a positive reflection occurs and the signal is travelling back to the beginning of the line. This measurement principle is often referred to as "Time Domain Reflectometry". In this thesis this principle is used to measure the water content of soil by using a transmission line as sensor element and a suitable miniaturized electronic measurement circuit is developed. In addition the Time Domain Reflectometry measurement principle is investigated for tissue recognition at the tip of a needle.

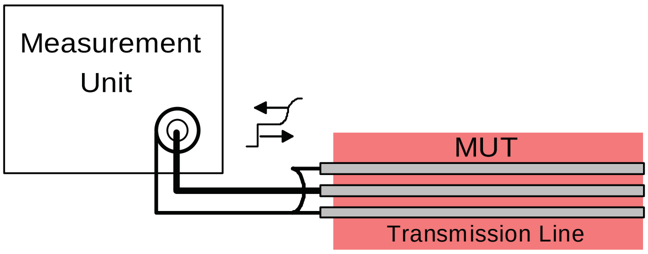

Figure 1.14: Measurement of electric and dielectric parameters of a MUT using an embedded open ended transmission line. The geometry of the line is designed in such a way that a large fringing field is penetrating the surrounding media.

If only high frequency signals are of interest it is sometimes possible to use optimized antennas for sending electromagnetic waves towards the MUT and for receiving either the transmitted or the reflected signals. Figure 1.15 A shows a typical setup for transmission measurement and Figure 1.15 B shows a typical setup for reflection measurement. Target applications for this method are mainly found in the field of moisture measurement where free and bound water molecules interact with high frequency microwave signals. For low frequency applications such as e.g. broadband impedance analysis of biological cells and tissue this method is not suitable due to the resulting large wavelengths of the signals.

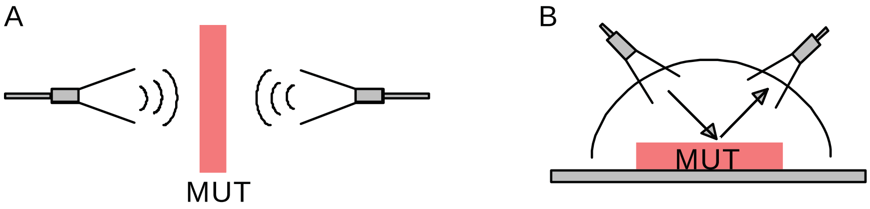

Figure 1.15: Free space measurement of dielectric properties of a MUT using two antenna positions. In A a setup for a transmission measurement is shown and in B a setup for a reflection measurement is shown. All antenna based setups are only suitable at high frequencies in the microwave range.

1.6 State of the Art in Impedance Spectroscopy Measurement Circuits and Systems

Broadband impedance spectroscopy as a measurement method can only be successfully employed in real applications and products when there is a suitable electronic measurement circuit or system available. Conventional expensive laboratory measurement equipment does not fulfil the typical requirements of small size, low cost, low power consumption and simple integration into the target application. The interesting frequency range for different applications reaches from below 1 Hz up to several 10 GHz which means a potential bandwidth of approximately 10 decades. Of course there is almost no technical, physical or biological application where the entire frequency range is of interest. This automatically implies that it absolutely makes sense to classify different applications according to their corresponding "frequency windows". Within these frequency windows there are individual interesting frequency dependent properties of the MUT which allows to derive interesting information about the state of the MUT. Now it makes sense to develop efficient electronic measurement circuits and systems which are able to measure within such a defined frequency window. This allows for optimizing the system by setting appropriate boundary conditions for the electronic circuit. However, sometimes it is still a challenge to develop a broadband measurement circuit which covers several decades of frequency when a special boundary condition such as e.g. extremely fine resolution of amplitude or phase shift has to be measured or if the measurement of the whole impedance spectrum must be accomplished within a very short period of time. Unfortunately the individual boundary conditions vary from application to application and in many cases this does not allow to reuse circuits. It would be very efficient to have one or more concepts for universal electronic measurement circuits which can be employed "out of the box" for a variety of applications with a minimum of changes. In the ideal case there would be a set of adjustable parameters only which allow to set the measurement circuit properties such as e.g. bandwidth, measurement time, resolution or the measurement signal amplitude. In the past when the first broadband impedance measurement experiments have been done there was only the option to build analog measurement circuits. Of course analog circuits may lead to a good measurement result but it is almost impossible to optimize analog circuits in such a way that they could be reused by changing parameters only. Nowadays the situation is different: there are many programmable electronic devices available at very low cost which offer new and attractive options for smart measurement concepts and circuits. It is possible to add flexibility to the circuit by employing software e.g. inside a Microcontroller (MCU) or Digital Signal Processor (DSP) or by using reconfigurable logic devices such as Complex Programmable Logic Devices (CPLDs) or Field Programmable Gate Arrays (FPGAs). In combination with an optimized analog front end which forms the "bridge" to the electrodes on the MUT it is now possible to use complex measurement signals and process measurement results with efficient signal processing methods optimized for the employed signals.

In many scientific articles (see below) broadband impedance measurement is performed with a custom made measurement setup. One common method is to use programmable measurement components such as AD-Converter modules and DA-Converter modules with an interface connection to a host computer. As an alternative standard oscilloscopes and arbitrary waveform generators are used for signal generation and acquisition. The computer is controlling the measurement setup and is processing the acquired measurement signals. Main reasons for building up such individual measurement systems are often the need for an optimized analog front end to the MUT or optimized measurement signals, methods and strategies which have application specific advantages compared to standard laboratory measurement equipment such as e.g. LCR-Meters. Pliquett et al. proposed such a computer based system for fast time domain based impedance measurement of biological tissues [56]. Kozlowska et al. analysed electric and dielectric properties of biological tissue within a test cell based on a computer controlled setup [57]. Xu et al. propose a computer controlled setup for sensor readout in structural health monitoring applications [58]. Maertens et al. developed a measurement system for fast broadband readout of piezo sensors [59], Hoja et al. developed a computer based system for anti corrosion coating spectroscopy based on pulsed measurement signals [60] and Lentka et al. show how to efficiently obtain an impedance spectrum based on Laplace Transform algorithms for a computerized measurement system [61]. Palani et al. demonstrate how to build a computerized high resolution measurement system for the broadband characterization of transformers [7]. Da Silva et al. developed a system for high speed measurement of the complex permittivity of fluids [18] and Yoo et al. developed a computer based impedance spectroscopy system for real-time measurement of complex impedances of a MUT within electrochemical experiments [2]. In all named applications there are interesting aspects and ideas for optimized measurement of the broadband impedance, but all these systems are quite expensive and bulky and are far away from being integrated into a real product. In most scientific articles a new measurement approach is examined and verified within experiments, but there is no transfer of the whole system into a small and efficient electronic circuit which could be incorporated into cost sensitive products.

Several other scientific articles elaborate on the optimization of the analog front end which is usually employed between the sampling circuit (e.g. AD-Converter or laboratory instrument) and the electrodes. Typical circuits deal with the development of stable and error free broadband current sources or impedance matching circuits. Yelamos et al. present an amplifier circuit for improving the measurement range and accuracy of a conventional laboratory impedance analyser within measurements on biological tissue samples [62]. Aroom et al. developed a universal electronic front end circuit based on a modified Howland Bridge [63], Mathis et al. developed a measurement circuit for cross correlation based impedance estimation [64]. Almasi developed a measurement front end circuit for precision very low frequency measurements [65]. Seoane et al. developed an optimized wideband current source circuit based on a single operational amplifier [66] and Weereld et al. developed a circuit for bipolar pulsed measurement of impedances within tomography applications [67]. There are several more interesting circuits and front ends proposed in the literature, but all of them can only be used in combination with a complete measurement system comprising a signal source and a signal acquisition module as often found e.g. in a computerized measurement setup. In some cases the researchers developed a whole measurement system which is mainly intended to be used in the laboratory only. Such equipment may give precision measurement results but is usually not optimized for low cost, small size and low power consumption. Examples for such custom build laboratory systems are the multi channel measurement systems developed by Thiel et al. [68] and Hartov et al. [69]. A very interesting and promising approach for a modular broadband impedance measurement unit is the IMPSPEC system. Nacke et al. and Pliquett et al. present the functionality and the system concept within several scientific and technical articles [30, 70–72]. The system is developed as a real product which can be used "out of the box" for various applications. The different frequency ranges are covered by different measurement principles and signals. For instance the system can measure at low frequencies by applying (multi) sinusoidal measurement signals and it can measure at high frequencies up to a few GHz by applying Maximum

Length Sequence (MLS) signals. In contrast to many computer based measurement setups the IMPSPEC system is capable of processing the measurement signals by built in logic modules and processors. The IMPSPEC system is a powerful and precision system which can be considered as a "bridge" between conventional computer based systems and a standardized measurement unit dedicated for impedance spectroscopy. However, the IMPSPEC system is still too large in size for several applications such as e.g. wearable medical and textile products. In addition the price is too high for mass production and integration in consumer products. In most cases only certain special applications or industrial processes can justify the high price of the system which is in the range of several thousand Euro depending on the individual system configuration.

Within the last 5 to 10 years there was some progress in the development of electronic platforms and concepts for efficient broadband impedance measurement. All platforms and systems which are presented in the literature show several identical aspects: they employ modern and powerful programmable devices such as Microprocessors, Digital Signal Processors or Field Programmable Gate Arrays. All developed circuits have the same idea of optimizing the overall system by combining efficient and smart measurement signals and fast and robust signal processing algorithms. One very interesting and promising approach is developed by Schneider at al. [73]. The presented system measures with a sinusoidal signal which can arbitrarily be adjusted in frequency. The signal is sampled by conventional AD-Converters and is then processed with optimized algorithms. One key consideration of this system is to enhance the signal to noise ratio (SNR) by employing oversampling and by fitting sinusoidal functions to the sampled signal points. The system is intended to be used in industrial measurement applications e.g. in combination with capacitive sensor front ends. However, although this system shows several positive aspects, there are some major drawbacks. One drawback is the required long measurement time because the sinusoidal excitation signal has to be swept over the entire frequency range of interest. This prohibits to use the system in fast or dynamic applications. A second drawback may be the employed direct sampling scheme of the signals. It is a straight forward approach but causes a relatively complex electronic circuit which is capable to handle the resulting high data rates. Memory space and signal processing power must be adjusted to the large amount of raw data. In addition the resulting power consumption of the system will be relatively high. Other interesting broadband impedance measurement platforms are developed by Min et al. [74–76]. The authors propose new concepts especially for a simplified excitation signal design and corresponding effective signal processing concepts. The presented electronic prototype system employs a fast DSP for calculation of cross correlation functions and the Fast Fourier Transform (FFT). Due to the proposed different excitation signals the system is quite flexible and shows good potential for further optimization and miniaturization. One potential drawback might be the required signal processing time in very fast applications. Here the serial processing of the captured raw data is a potential limitation in the current architectural design of the system. However, the platform has potential to be enhanced in terms of processing speed by replacing the serial data processing path by a parallel processing concept implemented e.g. inside a standard FPGA. In addition to these systems the authors already proposed a FPGA based concept for high speed measurements for biomedical applications [77]. Here synchronous sampling of a repetitive waveform is employed as a measurement concept. The concept has great advantage compared to several traditional systems, but the synchronous sampling scheme is limited in its flexibility because it is not possible to excite any frequency of interest without violating the fundamental working concept of the proposed efficient data processing. This might be a limitation in applications where a narrow frequency band has to be captured with a high frequency resolution e.g. in resonant circuits, crystals or piezos. Other FPGA based impedance measurement applications are presented by Patz et al. [78] and Yoo et al. [79]. The system developed by Patz is intended for use in multichannel applications such as tomography and is capable of sampling up to 14 channels. The developed system is relatively slow and a few hundred milliseconds are required for the impedance measurement and signal processing. The system is not optimized for size, cost and power consumption. The FPGA based system proposed by Yoo et al. is based on a very traditional sinusoidal measurement signal source and traditional direct sampling of the voltage and current signals. The processing is done by a FPGA and a DSP. The overall circuit complexity is very high compared to the obtained speed and accuracy. A much smaller system with even better accuracy, resolution and a higher bandwidth is proposed by Beckmann et al. [80]. The small system is based on a cheap standard microcontroller and the size of the electronic circuit is very small compared to most other systems and solutions. The miniaturized system is also using sinusoidal measurement signals and is optimized for a frequency window starting at a few kHz and ending at 1 MHz. Target application of the circuit are battery powered wearable textiles with integrated electrodes. The system looks attractive for such applications especially because of the expected low production price of the electronic circuit. However, because of the employed sinusoidal sweep the system is slow and can only be used for static or quasi static applications. Last but not least there is the option to embed a full broadband measurement system into one single chip. This allows for the smallest size and gives very good options for optimizing the power consumption. Lerch et al. developed a programmable Mixed-Signal ASIC for data acquisition systems in medical implants [81]. The circuit contained flexible measurement options, integrated data storage options, a wireless communication interface and various additional functions such as watchdog and power management modules. Another interesting system is currently commercially available on the market (AD5933 from Analog Devices [82]). The integrated circuit AD5933 is tested in various applications and the results are published in the literature [83–85]. According to the different authors and the datasheet there are several limitations of the circuit. Most significant limitation is the frequency range which allows to measure only up to 100 kHz. This is usually not enough for many applications such as e.g. biomedical tissue analysis or biological cell analysis. Second limitation is the requirement for relatively complex external amplifier circuits. Of course it is possible to build such amplifier circuits, but then the great advantage of having a complete system on one single chip is lost. In addition the price for the AD5933 is very high (in the range of approximately 30 Euro per chip) which prohibits to use the chip in cost sensitive applications. Sachs et al. developed an interesting and promising ultra wideband measurement circuit based on MLS-Signals for measuring within an extraordinary large frequency window reaching from near zero up to approximately 5 GHz [45]. But the presented chip mainly contains the components for signal generation and sampling and therefore requires an additional external processing system. Yufera et al. developed a chip for measuring the impedance of a 2D array of biological cells [86]. All components of the measurement system including the electrodes are manufactured on one chip. The measurement system is interesting for a small number of applications only because the integrated measurement electrodes can not be connected to external hardware such as external electrodes or external amplifier circuits.

In summary the literature survey shows that there is still a broad gap between state of the art experimental laboratory measurement equipment and the requirements which are given by most practical applications. A few interesting approaches for lightweight measurement systems and smart signal processing methods have been published yet but the large amount of potential target applications and its individual requirements currently cannot be covered by these techniques. Goal of this thesis is to fill the existing gap by developing smart measurement concepts which can be used for real products especially when it comes to requirements such as low cost, small size and low power consumption. A detailed analysis of many potential target applications shows, that there are mainly two groups of applications. In a first group there are static or quasi static applications where the measurement time is not critical but in many cases a high accuracy and high resolution of the measurement result is required. The second group of applications are mainly fast and dynamic systems which require to measure and process impedance data within a very short period of time. In order to derive optimized measurement strategies and universal electronic circuit concepts for all applications it makes sense to distinguish at least between these two groups of applications and develop an individual optimized measurement platform for each group. Within this thesis the focus is on target applications in the field of biomedical engineering and environmental engineering. Two biomedical applications have been investigated in detail and the developed electronic circuits have successfully been tested within these applications. In addition one environmental engineering application has been analysed and a miniaturized version of one measurement circuit has successfully been developed. The applications are examined in chapters 2 and 3 of this thesis, the developed two measurement concepts and the electronic circuits are discussed in detail in chapter 4.