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Integrated dielectric spectrometer for wideband and high-speed measurements using pseudo-noise codes

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Abstract. The paper gives a short introduction into some system-theoretic aspects and features of dielectric measurements by periodic wideband signals. Based on these considerations, a related measurement concept will be presented which is well suited for both compact device implementation and monolithic integration. Some implementation examples are shown and first measurement results are presented.

1. Introduction

"Broadband Dielectric Spectroscopy (BDS) is besides Nuclear Magnetic Resonance (NMR) spectroscopy the experimental tool to study molecular dynamics in a broad frequency (10^{-6} Hz to 10^{11} Hz) and temperature range. It has the additional advantage that the sensitivity of the measurements increases with decreasing separation of the electrodes and hence with decreasing amount of sample material." [2]

Seen from the viewpoint of the measurement device, such a setup involves the capturing of weak signals in order to avoid overloading of the test sample. Since recent measurement devices are still quite bulky, they have to be connected with the measurement cells via cables. They introduce an additional parasitic impedance and a signal transformation affecting, e.g., the wanted impedance of the measurement cell. In order to remove these uncertainties, a calibration of the measurement setup may be performed. However, every variation of the setup due to cable bending (leading to variations of propagation time and triboelectric current generation), temperature variation or temperature gradient etc. will degrade the calibration and hence it will reduce the reliability of the measurement. In order to alleviate the susceptibility of dielectric measurements to such influences and to break the restraints of the 50 Ω environment for RF-measurements, the actual measurement plane has to be moved as close as possible towards the electrodes of the measurement cell. This is best done by monolithic integration of the critical device components.

Furthermore, the field exposure of the device or material under test (DUT, MUT) and the measurement speed may be critical issues if small volumes and a plenty of items must be continuously evaluated. This requires sounding signals of low crest factor and a wide instantaneous bandwidth. Binary pseudo-noise (PN) codes (in particular the M-Sequence) represent a signal which meets these requirements. They may be generated by a simple and stable approach providing a large fractional bandwidth. In the future, this will open the way to join micro-fluidic devices and wideband measurement electronics on a single chip (Lab on a Chip).

In what follows, we shortly introduce some system-theoretic aspects and features of dielectric measurements by periodic wideband signals. Based on these considerations, a related measurement concept is presented which is well suited for compact device implementation and monolithic integration, as well. Some implementation examples – restricted to the RF-domain for the sake of shortness – are shown and first measurement results are presented.

2. Dielectric measurement based on signals of large fractional bandwidth

The polarization behavior and conductivity of a material under test (MUT) are usually summarized by the frequency dependent complex permittivity $\underline{\varepsilon}(f)=\varepsilon_0(\varepsilon_r'(f)-j\varepsilon_r''(f))$ (ε_0 - permittivity of vacuum, $\varepsilon_r', \varepsilon_r''$ - relative dielectric constant of the MUT - real and imaginary part; complex quantities are denoted by underlined symbols). The determination of the permittivity is based on specimen-holders or measurement setups which represent either one- or two-port systems. A summary of different measurement configurations is given in [1]. Depending on the operational frequencies, the behavior of these devices is typically described by impedance $(\underline{Z})$ or admittance $(\underline{Y})$ functions and scattering parameters $(\underline{S})$. To abstract from the different options, we write the relations between the measured signals and the characteristic functions of the test setup as:

$$\underline{P}(f)=\underline{Q}(f)\,\underline{R}(f) \tag{1}$$

in which $\underline{Q}=\underline{Q}(f,\underline{\varepsilon}(f),\mathbf{\Theta})$ stands for $\underline{Y},\underline{Z},\underline{S}$ -parameters. $\underline{Q}$ may be a scalar quantity or a matrix whose entries depend on frequency f, the geometric structure of the test setup (symbolized by the vector $\mathbf{\Theta}$ containing geometric parameters; corresponding relations can be found in [1, 3]) and the permittivity $\underline{\varepsilon}(f)$ of the MUT. $\underline{P}$ and $\underline{R}$ represent the measured quantities (i.e. voltage, current or normalized waves) who may be either a scalar or a column vector. In order to gain $\underline{\varepsilon}(f)$, we have to calculate $\underline{Q}(f)$ from the measurements first. This is simply done by:

$$\underline{Q}(f)=\underline{P}(f)/\underline{R}(f) \tag{2}$$

Relation (2) extends to a related matrix operation in the case of a two port test setup (see chapter 2.5.4 in [4]). The complex notation in (1) and (2) assumes the measurement of signal magnitudes and phases. Since this is only feasible for sine waves, both relations cannot be immediately applied for arbitrary wideband signals. Instead of (1), we have to write a convolution

$$p(t)=\int_{-\infty}^{\infty} q(\tau)\,r(t-\tau)\,d\tau = q(t)*r(t) \tag{3}$$

in which $p(t)$ and $r(t)$ represent the measured wideband signals of arbitrary shape and $q(t)$ is the impulse response function of the test setup containing the wanted information about $\underline{\varepsilon}(f)$ since $\underline{Q}(f)=\mathfrak{F}\{q(t)\}$ (with $\mathfrak{F}\{\ \}$ denoting Fourier Transform). Due to the limited recording time T_R in the case of a real measurement, (3) actually becomes:

$$p(t)=\int_{-T_R/2}^{T_R/2} q(\tau)\,r(t-\tau)\,d\tau=\left[\mathrm{rect}\left(\frac{t}{T_R}\right)q(t)\right]*r(t) \xrightarrow{\mathfrak{F}\{\ \}} \underline{P}(f)=\left[\underline{Q}(f)*\mathrm{sinc}(f\,T_R)\right]\underline{R}(f) \tag{4}$$

Hence, the wanted $\underline{Q}(f)$ is affected by a sinc-function. As shown in [4], its influence can be eliminated by choosing periodic wideband signals of period T_0 for which $T_R=n\,T_0;\quad n\in\mathbb{N}$ holds.

In order to estimate $\underline{Q}(f)$, we subject the measured signals to a Fourier Transform and apply (2). However, it becomes ill-conditioned at higher frequencies due to the lack of spectral components at the upper end of the stimulus spectrum. Unfortunately, this spectral gap has to be accepted since we have to enforce the Nyquist theorem by anti-aliasing filters which will never have abrupt edges. By regularization (see [4]), the ill-conditioned problem may be suppressed up to a certain degree.

3. Pseudo noise measurement device

The PN-device as depicted in Figure 1 exploits the above introduced wideband approach for dielectric measurements in frequency and time domain. A stable clock generator pushes a binary shift register which provides the PN-sequence (M-sequence). This signal –having a comb spectrum – stimulates the MUT. Bandwidth and spectral line spacing are fixed by the clock rate and the shift register length. In contrast to the classical sine wave approaches, the measurement may run quite fast since all spectral lines appear in parallel. A sampling receiver captures the measurement signal. They are processed to give either $\underline{Q}(f)$ or $q(t)$. In subsequent steps, one has to extract the wanted information about the MUT. The low pass-filters in Figure 1 are aimed to keep the Nyquist sampling theorem and the

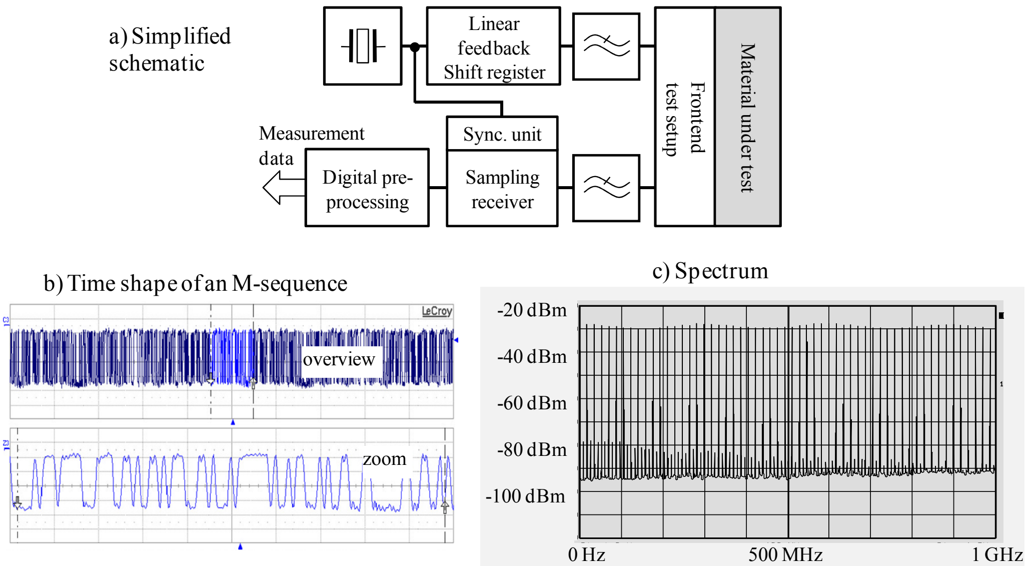

Figure 1: Simplified schematic of a PN-device for one-port measurements and typical appearance of a PN-signal in time and frequency domain

frontend is either a directional bridge or an auto-balancing bridge depending on the considered frequency band. For two-port measurements, one needs a multi-channel version of the PN-device. The interested reader is addressed to [4] for further discussions of the device functioning and performance.

4. Implemented devices and measurement examples

For the sake of shortness, we only refer to two RF-examples even if the measurement method is not restricted to that domain only. Figure 2 shows the structure and a photo of an integrated RF-frontend. It is a key component of a small device for reflection factor measurements as depicted in Figure 3. Due to its small volume and weight, a coaxial probe can be immediately connected to the device.

The second example refers to a transmission line measurement and data evaluation in time domain. Figure 4 depicts the measurement schematic und shows some results. We measured the transmitted impulse response function of a coplanar waveguide which was in contact with a liquid under test. The liquid was running through the test fixture in portions (assigned by capital letters A ... F). For the sake of demonstration, we simply used saltwater with minor variations in salt concentration, fresh and distilled water (all of same temperature). As expected, the measurements have shown that mainly the peak value of the pulse was affected by the different salt concentrations. In other experiments, the temperature of fresh water was slightly changed. Now, pulse position, pulse width and magnitude have changed due to permittivity variation. A rough estimation has shown that temperature variations of water are traceable down to $5{\cdot}10^{-3}$ °C with the applied prototype device.

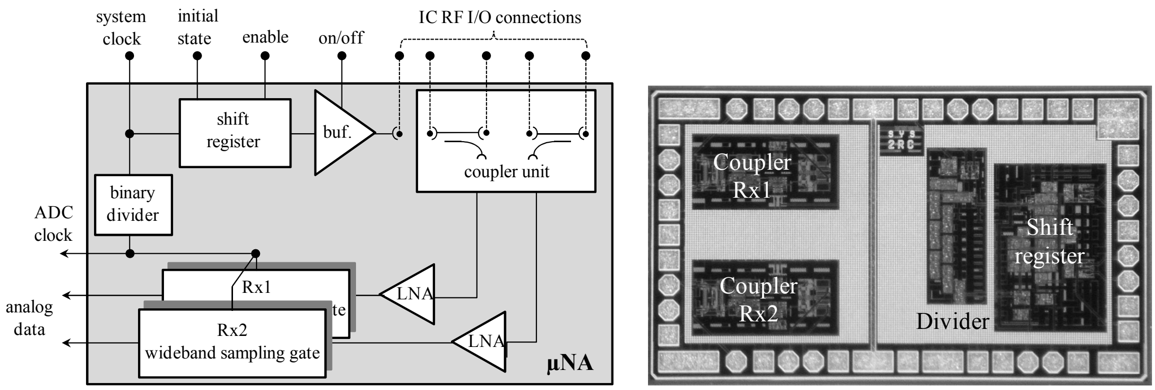

Figure 2: Structure of the RF-part and microphotograph of an integrated PN-sequence device

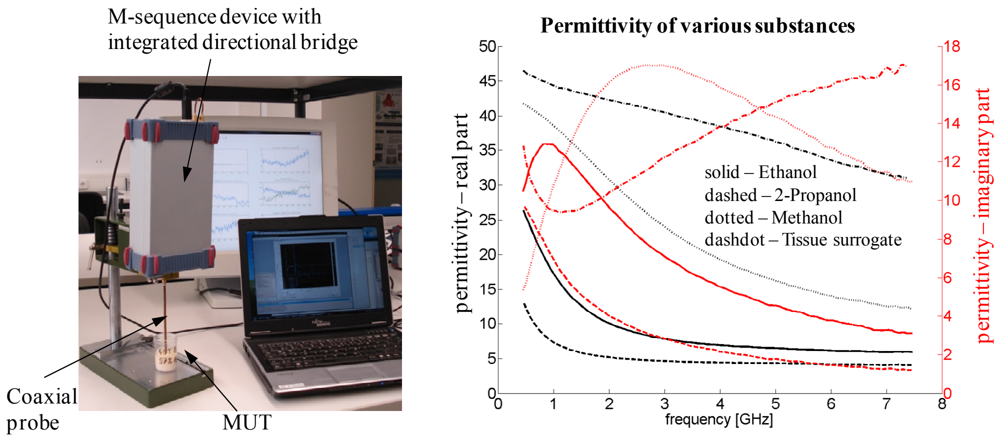

Figure 3: Example of permittivity measurement by a coaxial probe

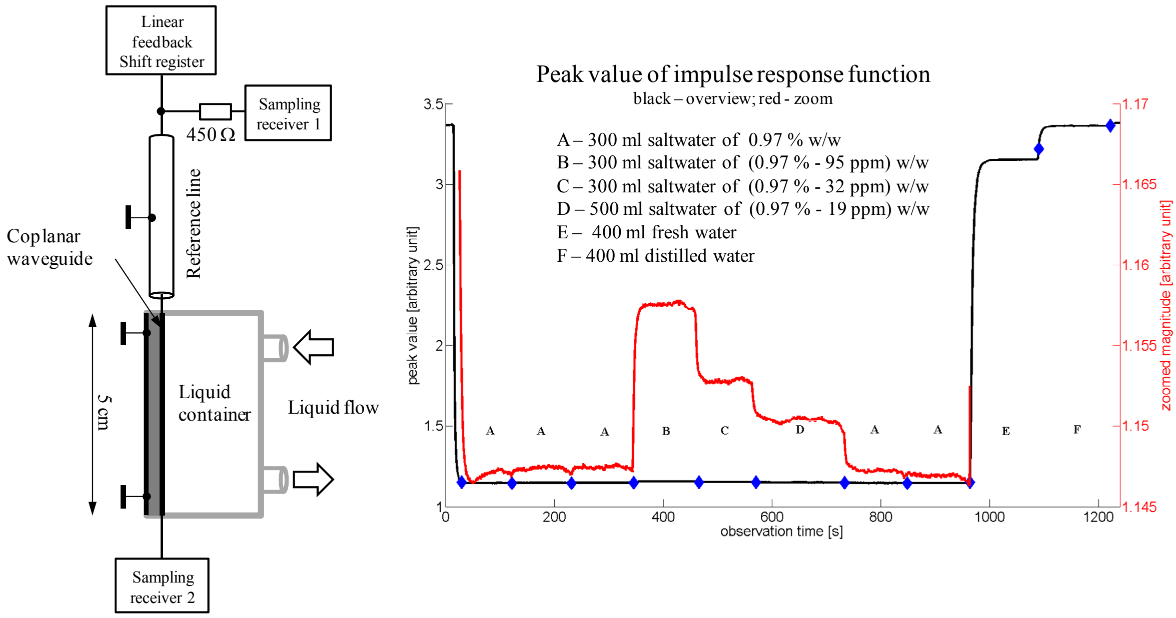

Figure 4: Continuous time domain measurement for tracking of permittivity variations.

5. Conclusion

Dielectric spectroscopy based on M-sequence signals represents an interesting alternative to the classical sine wave approaches. The devices promote monolithic integration of key components and permit the construction of small and light weight equipment for precise and continuous observation.

References

[1] Kremer F, Serghei A, Sangoro J R, Tress M, and Mapesa E U 2009 Broadband Dielectric Spectroscopy in nano-(bio)-physics *IEEE Conference on Electrical Insulation and Dielectric Phenomena, CEIDP '09*, pp. 1-6.

[2] Baker-Jarvis J, Janzic M D, Riddle B F, Johnk R T, Kabos P, Holloway C L, Geyer R G, and Grosvenor C A 2005 Measuring the Permittivity and Permeability of Lossy Materials: Solids, Liquids, Metals, Building Materials, and Negative-Index Materials *NIST Technical Note 1536*.

[3] Kupfer K 2005 *Electromagnetic aquametry: electromagnetic wave interaction with water and moist substances*. (Berlin, New York: Springer)

[4] Sachs J 2012 *Handbook of Ultra-Wideband Short-Range Sensing - Theory, Sensors, Applications*. (Berlin: Wiley-VCH)