35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

A Wideband Scalar Network Analyzer for Biomedical Dehydration Measurements

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***Abstract*—This paper presents a wideband microwave approach towards biomedical dehydration monitoring. The introduced concept is verified via invasive measurements on several blood samples. A microwave measurement circuit, based of a two-port scalar vector network analyzer is presented. The circuit operates between 5 GHz and 20 GHz using a planar permittivity sensor. Measurements of all subcomponents are shown together with measurements of a Water-NaCl-Glycerol solution.**

I. Introduction

Dehydration is a leading cause of hospitalization among elderly people and plays an important role in an aging society. By dehydration a loss of autonomy and cognitive functions is indispensable for humans [1]. Thus it is of major interest to accurately monitor the hydration status. Furthermore this application will not be limited to elderly people only. Another important application could help athletics that might suffer from dehydration in sport. In this paper a microwave based concept for precise measurement of water content in aqueous solutions is proposed.

II. Concept

The dielectric relaxation process describes the properties of a material under test (MUT) which is excited with an external electrical field. The dielectric relaxation can thus be used to characterize the condition of a certain material, solution or emulsion. A Debye relaxation process can be described as denoted in Eq. (1) for aqueous solutions [2]. Where ϵ_∞ is the permittivity at high frequencies, ϵ_{stat} is the static, low frequency permittivity, and τ is the characteristic relaxation time of the MUT.

$$\underline{\epsilon_r}(\omega) = \epsilon_\infty + \frac{\epsilon_{stat} - \epsilon_\infty}{1 + j\omega\tau} \qquad (1)$$

The permittivity can be measured using different techniques such as coaxial or transmission based sensors. Both methods make use of fringing electric fields that penetrate a MUT. By a change in water content of a MUT, a variation of the fringing fields can be measured in magnitude and phase. In this paper, a microwave based approach is proposed to determine the water content within a MUT by measuring the attenuation over concentration. The amount of water in an emulsion or aqueous solution, such as blood, will increases the transmission losses through the MUT. It is proposed to use this effect to determine the water content, which can be used for dehydration detection.

III. Invasive Verification and Modeling

The proposed influence of water content in blood samples has been proven by invasive experiments. The measurement setup for this experiment is illustrated in Fig. 1. The permittivity of different blood samples has been measured over different water concentrations. The water content has been changed by manual dispensing. Fig. 2 shows the influence of an increasing water content on the permittivity of blood. Since invasive measurements with human blood samples are highly extensive, a substitute solution for further measurements was evaluated. It is shown in Fig. 3 that a NaCl-Water solutions with a variable Glycerol concentration has comparable dielectric properties and could replace blood samples in further experiments.

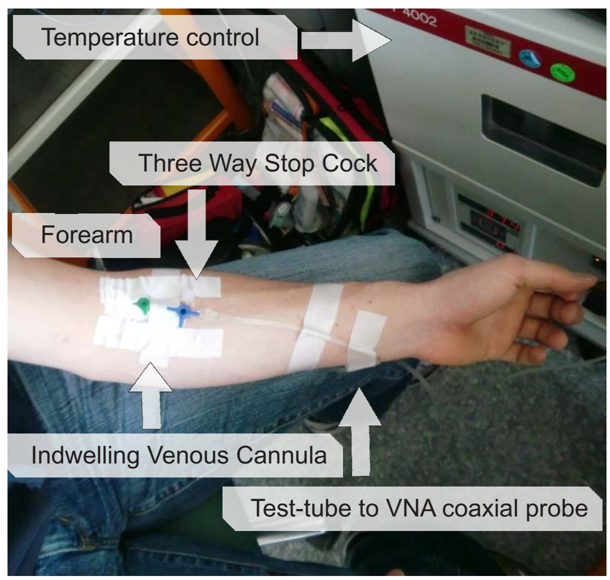

Fig. 1. Invasive measurements on blood samples of 2 ml with temperature controlled equipment with insert indwelling cannula and three-way stop cock (approval from the Ethical Review Committee (ERC) has been obtained).

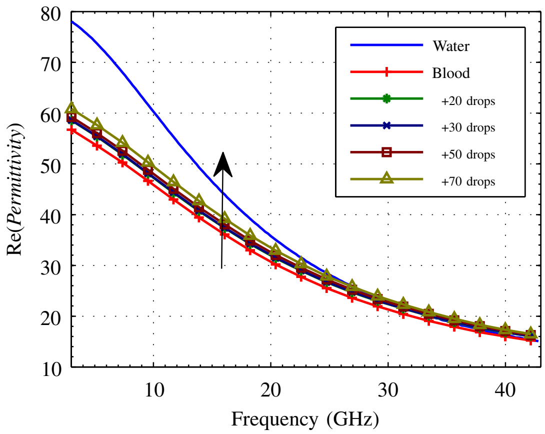

Fig. 2. Real part of the measured permittivity of the 2 ml blood sample, obtained with a conventional vector network analyzer *(Agilent PNA-X with coaxial probe)* and a drop volume of approximately 20 µl.

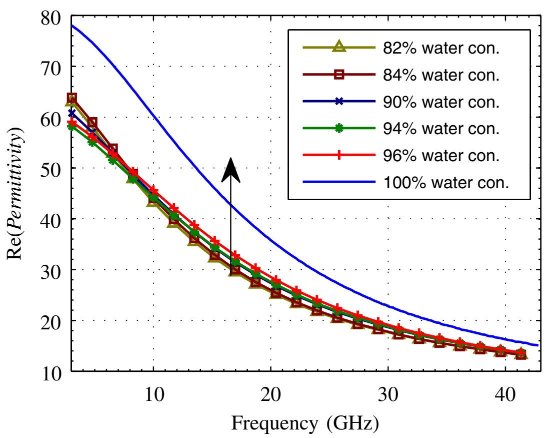

Fig. 3. Real part of the measured permittivity of the NaCl-water-glycerol mixture, obtained with a conventional vector network analyzer *(Agilent PNA-X with coaxial probe)* over several concentrations.

IV. Circuit Design

Concentration measurements using transmission based sensors for biomedical application were introduced in [3] and [4]. Those methods are based on the wideband determination of complex scattering parameters of the sensor or transmission line, respectively. This work shows that a compact scalar network analyzer could be used for dehydration detection in biomedical applications or evaluation of water content in liquids. The circuit concept is illustrated in Fig. 4, consisting of a permittivity sensor [4], two directional couplers [5] (fabricated in a reflectometer configuration) and three wideband power detectors, feeding the analog to digital converter (ADC). A wideband RF source feeds the material under test (MUT) with an incident wave between 5 GHz and 20 GHz with an output power less than 3 dBm. By the first directional coupler, approximately -15 dB is coupled out and used as a reference signal. The transmission and reflection at the MUT is fed to a power detector directly and through a directional coupler, respectively. The power detector consists of a passive multi section matching network and a zero biased detector diode. It is assumed that the transmission coefficient $|\underline{S}^*_{21}|$ of the

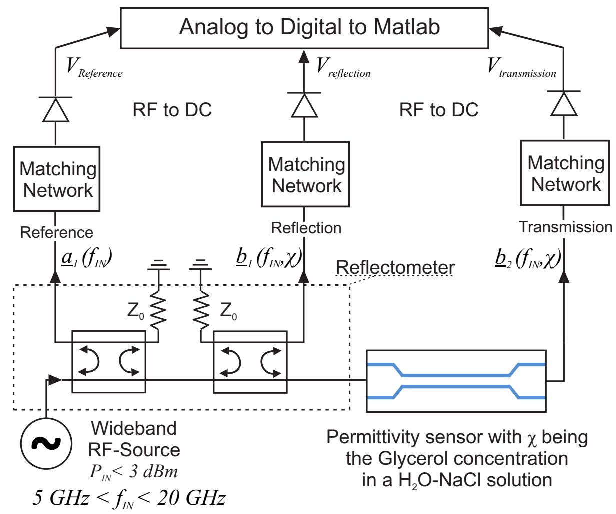

Fig. 4. Circuit concept for biomedical concentration measurements based on a microwave two port test set.

sensor will change with the water concentration χ in a test solution. An increasing water content will be followed by higher transmission losses which can be obtained according to Eq. (2).

$$|\underline{S}^*_{21}|\,(f,\chi) = \frac{|\underline{b}_2(f,\chi)|}{|\underline{a}_1(f)|} = \frac{V_{Transmission}}{V_{Reference}} \tag{2}$$

The transmission coefficients are subsequently determined in Matlab after a calibration procedure. The calibration function given in Eq. (3) is based on measuring four well known standards open, short, match, thru (OSMT).

$$|\underline{S}_{21}|\,(f,\chi) = \mathrm{Cal}(|\underline{S}^*_{21}|\,(f,\chi)) \tag{3}$$

For a suitable determination of the measured effect, all transmission coefficients are normalized to the lowest water concentration as denoted in Eq. (4) and summed over a frequency range between $f_{min} = 5$ GHz and $f_{max} = 20$ GHz.

$$\Delta\,|\underline{S}_{21}|\,(f,\chi) = \frac{|\underline{S}_{21}|\,(f,\chi)}{|\underline{S}_{21}|\,(f,\chi = 80\%)} \tag{4}$$

The result of this integration is frequency independent and shown in Eq. (5).

$$\mathrm{STC}(\chi) = \sum_{f=f_{min}}^{f=f_{max}} \Delta\,|\underline{S}_{21}|\,(f,\chi) \tag{5}$$

V. System Implementation and Measurements

All subcomponents of the introduced measurement system were fabricated and measured separately. One of the two directional couplers is shown in Fig. 5 with a cross section illustration (right). The reflectometer is based on two broadside coupled wideband directional coupler [5] in a four layer stack up. The measured properties of a single coupler are illustrated

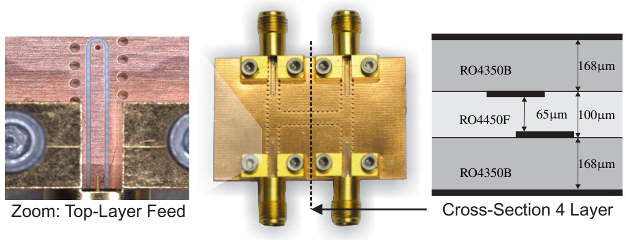

Fig. 5. Fabricated directional coupler on four layer Rogers *RO4350,4450* substrate.

in Figs. 6 and 7. One can obtain a return loss of approximately 20 dB and an insertion loss of approximately 5 dB over the entire frequency range. Further, a coupling and isolation of approximately 15 dB has been simulated and measured. For

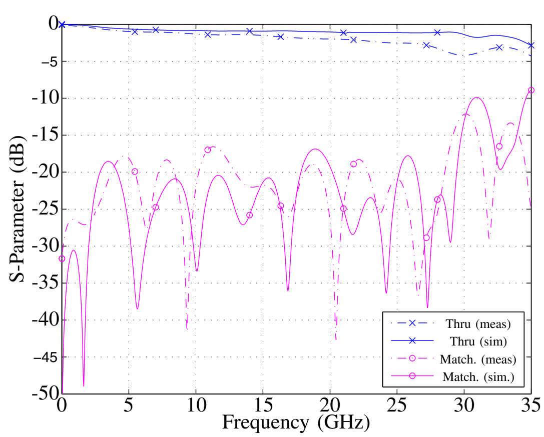

Fig. 6. Simulated and measured scattering parameters (matching and transmission) of a single directional coupler.

the measurement and reference channels, three power detectors were designed, fabricated and measured in the entire frequency range. A fabricated power detector is shown in Fig. 8. Two key parameter of the power detector are return loss and output voltage versus RF-Input power. Both are shown in Figs. 9 and 10 for simulation and measurement.

Fig. 11 shows the effect on Eq. 4 were one can obtain a clear relation in Fig.12 by the integration of Fig. 11 over the frequency as denoted in Eq. 5. The illustrated parameters are plotted in dB. As expected by theoretical investigations, the transmission coefficient decreases with an increasing water concentration due to the dielectric losses. This effect can be clarified by considering the sum of all determined transmission coefficients, which can be interpreted as the area above the curves of Fig. 11 and the frequency axis.

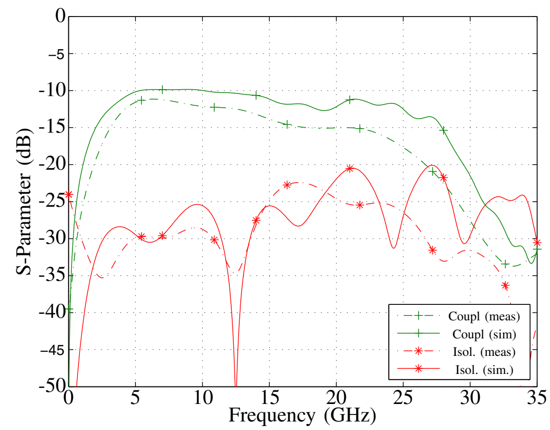

Fig. 7. Simulated and measured scattering parameters (coupling and isolation) of a single directional coupler.

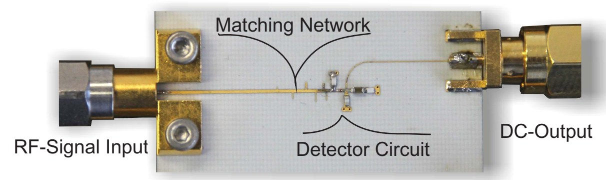

Fig. 8. Fabricated wideband power detector for applications up to 35 GHz.

VI. Error Discussion

As one can observe by the presented results, a high precision has been achieved, however minor errors can be read out. Those error could be based on time-invariant transmission properties of the permittivity sensor. Since the sensor suffers from minor water absorption.

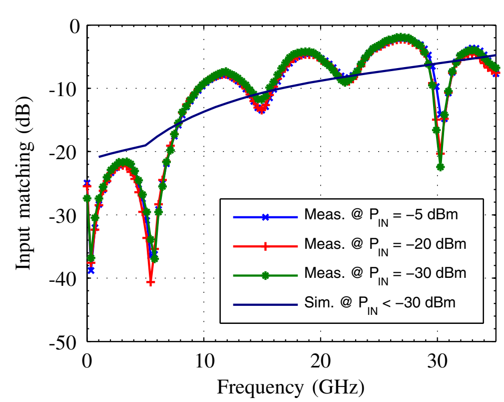

Fig. 9. Simulated and measured wideband RF power detector matching from 5 GHz to 35 GHz.

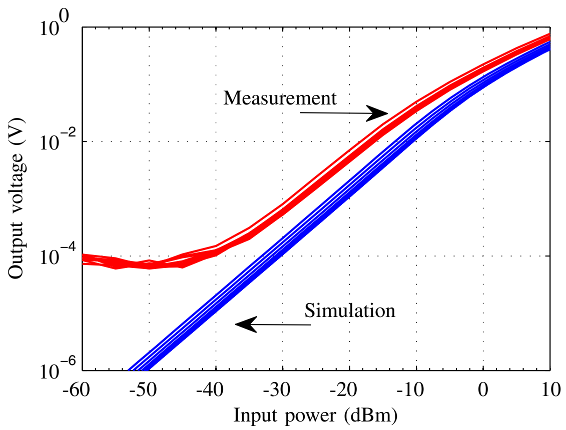

Fig. 10. Simulated and measured wideband RF power detector characteristic from 5 GHz to 35 GHz.

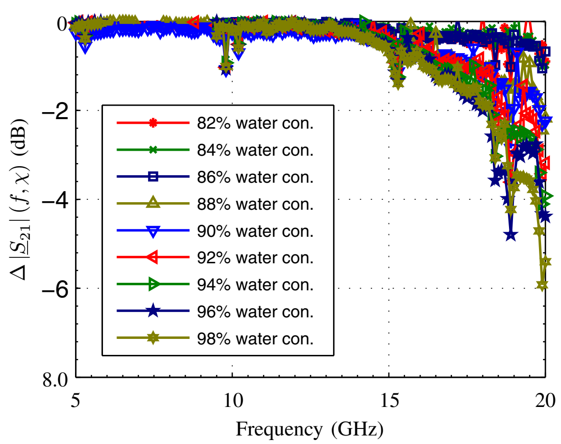

Fig. 11. Transmission parameter S_{21} over different water glycerol concentrations, normalized to the lowest glycerol concentration, obtained with the introduced scalar network analyzer.

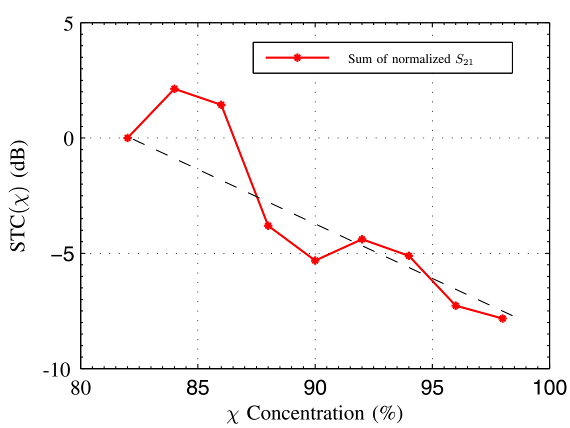

Fig. 12. Sum of the normalized transmission coefficients (STC) over the frequency range.

VII. Conclusion

In this paper a wideband microwave approach towards biomedical dehydration monitoring has been presented. The concept has been verified via invasive measurements on several blood samples. Further, a microwave measurement circuit, based of a two-port scalar vector network analyzer was presented. Measurements of all subcomponents of the device were shown together with measurements of a Water-NaCl-Glycerol solution. The overall measurement concept has been successfully shown.

Acknowledgment

This work has been supported by the German Federal Ministry of Education and Research (BMBF) through the research project SmartSensors within the excellence cluster Medical Valley EMN e.V. under contract number 01EX1014T.

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