A Multiband 2-Port Vector Network Analyzer based on Six-Port Junctions for Biomedical Measurement Applications between 6 GHz and 33 GHz

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***Abstract* — Concentration measurements of dissolved substances in fluids are of great interest for biomedical as well as industrial applications. In this work a multiband vector network analyzer is presented that is capable of determining phase variations due to changes in the concentration. A topology comprising two Six-Port networks optimized for the frequencies 6.6 GHz, 19.7 GHz and 32.4 GHz has been implemented. Measurement results show a characteristic change of the phase when increasing the glucose concentration in binary aqueous solutions.**

1 INTRODUCTION

In recent years the part of the population that is older than 60 years has been steadily growing, especially in the more developed countries [1]. This is due to an increasing life expectancy and low birth rates. It is important for elderly persons, but also for the entire society, that they are able to care for themselves even in an old age. Hence, a monitoring device is needed to continuously measure vital parameters. For this purpose research is conducted to develop a sensor for microwave based non-invasive measurement of blood parameters, for example the concentration of glucose. Such a monitoring system has many advantages over an invasive system in terms of safety and usability.

Also in the industry the continuous monitoring of concentration variations of dissolved substances in fluids is of particular interest, for instance during production processes. For these purposes many sensor technologies have been developed based on the change of the fluid's dielectric properties [2, 3, 4, 5]. Some of them are already available on the market, for example coaxial probes. However, the use of these sensors requires a vector network analyzer (VNA) to determine the complex scattering parameters which depend on the dielectric properties of the material under test (MUT).

Thus, in this work a multiband two-port VNA is presented, that is robust, low cost and can be easily integrated into a portable device. A Six-Port topology has been chosen because neither mixers nor additional local oscillators are required and because it features a high phase resolution due to its interferometric principle [6].

Section 2 gives a short overview of the sensor for microwave based non-invasive concentration measurements. Six-Port networks for multiband applications are discussed in section 3 followed by the system concept of the proposed VNA. Measurement results are presented in section 4.

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2 SENSING PRINCIPLE

In this work a coplanar waveguide sensor is used (Figure 1). The electromagnetic wave that is transmitted through the sensor has its fringing electric field partly located within the MUT on top of the structure. Therefore, the wave is influenced by the dielectric properties of the MUT [7]. This results in a change of the sensor's scattering parameters due to varying concentrations in the MUT, because the effective permittivity of the transmission line is modified. Since the MUT's influence varies over the frequency, the VNA that is presented here is designed to work in three frequency bands around $f_0 = 6.6\,\text{GHz}$, $f_1 = 19.7\,\text{GHz}$ and $f_2 = 32.4\,\text{GHz}$ as shown in Figure 2.

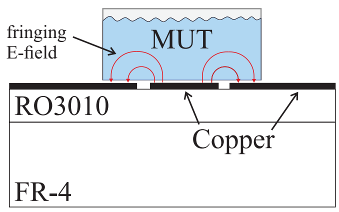

Figure 1: Schematic cross section of the utilized coplanar waveguide sensor.

3 SYSTEM CONCEPT

3.1 Multiband Six-Port Network

The well known Six-Port topology shown in Figure 3 is used in this project [8]. The circuit has been

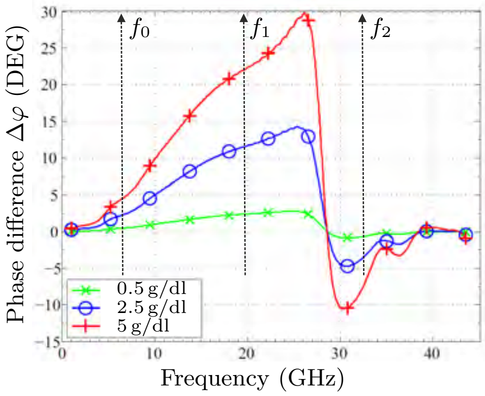

Figure 2: Simulated phase difference of the sensor's transmission coefficient due to glucose concentration variation.

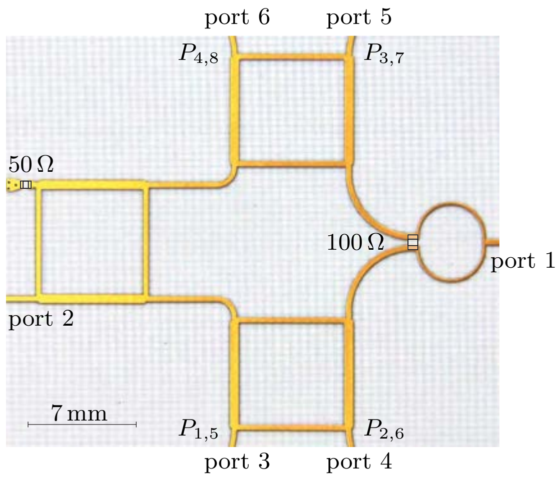

Figure 3: Photo of the Six-Port network realized in microstrip transmission line technology on a dielectric substrate (reflection: indexes 1 to 4; transmission: indexes 5 to 8).

designed and simulated using the software tools Agilent Advanced Design System and CST Microwave Studio with the time domain solver for wideband 3D electromagnetic field simulations.

The Six-Port junction comprises three 90° hybrid couplers and one Wilkinson power divider. The reference signal is connected to port 1 of the Six-Port whereas the wave that is reflected from/transmitted through the sensor is injected at port 2. The input signals are superposed under four different phase shifts (-90 DEG, 0 DEG, 90 DEG, 180 DEG). The resulting power levels at the output ports are P_1 to P_4 for reflection and P_5 to P_8 for transmission measurements. Thus, the phase φ of the transmission coefficient S_{21} of a device under test can be calculated with [8]:

$$\varphi = \arg\{S_{21}\} = \arctan\left(\frac{P_6 - P_5}{P_8 - P_7}\right). \quad (1)$$

Due to the periodic nature of microstrip transmission lines the characteristic behavior of the Six-Port network, that is equal power splitting and 90 DEG relative phase shifts between the output ports, can be achieved for the wavelengths $\lambda = \lambda_0 \cdot (2n+1)$, where λ_0 is the wavelength that corresponds to the fundamental frequency f_0 and $n \in \mathbb{N}$. Therefore, the Six-Port circuit can be used for phase measurements in multiple frequency bands [9]. However, it has to be noted, that the phase relation between the output ports 3 and 4 changes by 180 DEG from f_0 to f_1. Therefore, when using eq. (1) for measurements at 19.7 GHz the sign of P_5 and P_6 have to be changed.

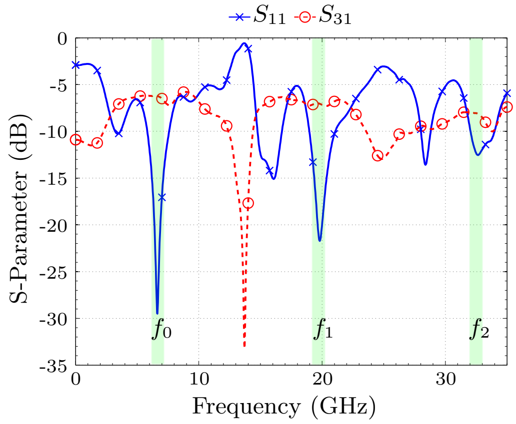

Figure 4: Simulated reflection and transmission coefficients of the Six-Port junction over the entire frequency bandwidth.

The simulated absolute values (dB) of the reflection coefficient at port 1 (S_{11}) and the transmission from port 1 to port 3 (S_{31}) with the considered frequency bands is shown in Figure 4. S_{11} is lower than -15 dB for f_0 as well as for f_1 and lower than -10 dB for f_2. S_{31} decreases with the frequency due to the increase of the electrical length and the finite conductivity of copper as well as the dissipation factor of the substrate.

3.2 Vector Network Analyzer

In order to achieve a simultaneous two-port measurement capability two Six-Port networks are used. As can be seen in Figure 5 the reference signal (RF_{in}) is split by a 90° hybrid coupler (H) and fed to the sensor as well as to the Six-Port networks ($6P_1$ and $6P_2$) via an additional Wilkinson power divider (WD).

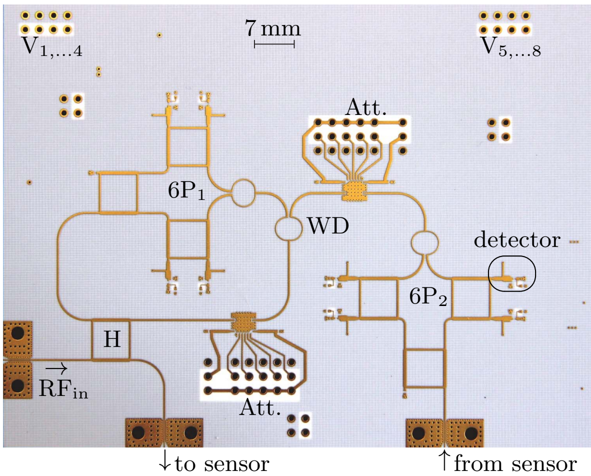

Figure 5: Photo of the designed multiband VNA.

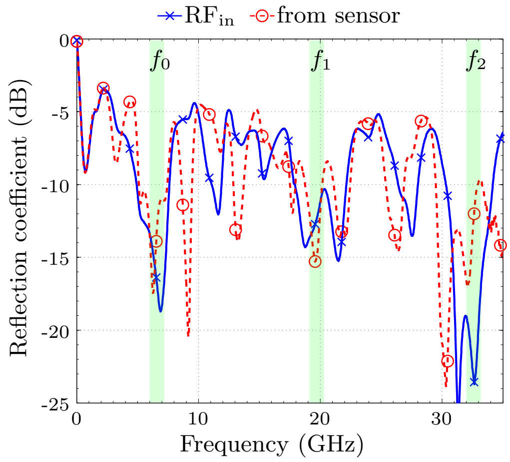

Figure 6: Measured reflection coefficients of the VNA's input ports.

Two 5-bit digital attenuators HMC941LP4 (Att.) from Hittite Microwave Corporation are used to adjust the power level of the reference signal to the power level of the reflected and the transmitted signal, respectively. The power level adjustment is necessary in order to operate the detectors in a quadratic region. Therefore, the measured voltages are linear with the RF power levels at the detectors. However, if only fluids with similar dielectric properties and losses are considered, the system can be implemented using fixed attenuators.

The reflected signal from the sensor is fed to $6P_1$ via the 90° hybrid coupler (H) whereas the transmitted wave is directly routed to $6P_2$. The radio frequency (RF) signals at the output ports are downconverted to DC with wideband Schottky diode detectors resulting in voltages $V_{1,\ldots 8}$. The DC voltages $V_{1,\ldots 8}$ can be easily digitized with analogue-to-digital converters and than post-processed for example using Matlab. Since $V_{1,\ldots 8}$ are directly related to the RF powers $P_{1,\ldots 8}$ the transmission coefficient's phase of a device under test can be calculated with eq. (1). For the phase of the reflection coefficient an equivalent equation has to be used.

4 MEASUREMENT RESULTS

The presented VNA as well as all subcomponents have been fabricated on a RO4350B dielectric substrate. The Six-Port network shows the desired relative phase shifts (-90 DEG, 0 DEG, 90 DEG, 180 DEG) with only $+/-3$ DEG tolerance for the frequency bands 6.6 GHz, 19.7 GHz and 32.4 GHz as demonstrated in Figure 8. The power imbalance between the output ports is only 0.98 dB for f_0 and not more than 2.6 dB for the highest frequency f_2.

The Schottky diode detectors have a very broadband characteristic with an input reflection coefficient lower than -10 dB for the considered frequencies. Figure 6 shows that the input ports (marked in Figure 5 with "RF_{in}" and "from sensor") of the VNA are well matched for f_0, f_1 and f_2.

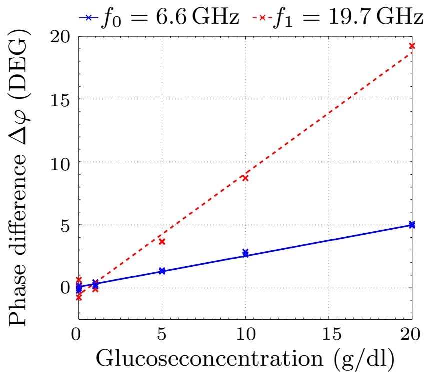

Figure 7: Measured phase difference of the sensor's transmission coefficient for varying glucose concentrations.

After a characterization of all subcomponents the multiband two-port VNA has been tested with the coplanar waveguide sensor at 6.6 GHz and 19.7 GHz. In a future development of this work the coplanar waveguide senor will be modified so that it can be also used for measurements at 32.4 GHz. The impact of the glucose concentration in binary aqueous solutions on the phase of the sensor's transmission coefficient is shown in Figure 7. The phase that has been measured with the presented VNA has a characteristic variation and can therefore be used as an indicator for the glucose concentration.

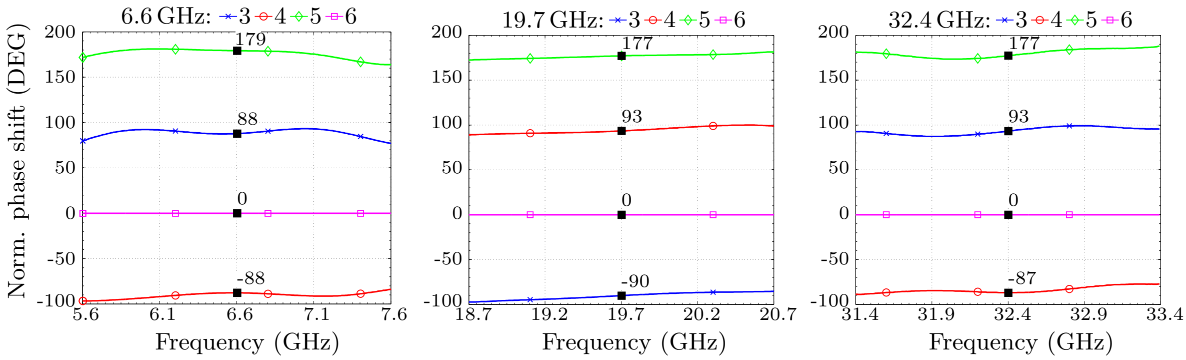

Figure 8: Measured relative phase shifts at the output ports 3 to 6 of the Six-Port network normalized to a phase shift of 0 DEG at port 6

5 CONCLUSION

The system concept of a multiband two-port vector network analyzer (VNA) for biomedical applications operating at 6.6 GHz, 19.7 GHz and 32.4 GHz has been presented. The VNA is based on a Six-Port topology and therefore no additional local oscillators or mixers are needed, which enables the implementation of low cost systems. Measurement results show that with this VNA and an appropriate sensor concentration variations of dissolved substances, for example glucose, in binary aqueous solutions can be determined.

Acknowledgments

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