Full 4-Port Characterization of SAW Duplexers with a 2-Port Network Analyzer

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***Abstract* — In this paper a switching network extension for a 2-port network analyzer is presented, which allows to determine the scattering parameters of SAW duplexers with three or four ports. The operational principle and the setup of the extension are illustrated. Some studies have been accomplished to analyze measurement accuracy and stability of the combined test equipment. In this context main focus is placed on the special requirements related to the measurement of SAW duplexers. The feasability of a reduced calibration procedure is examined. Finally measurement results of a SAW duplexer, obtained with the presented setup, are compared to reference data. A very good agreement can be observed.**

***Index Terms* — SAW duplexer, multiport measurement**

I. INTRODUCTION

The increasing prevalence of mobile communication implicates a simultaneously growing demand for characterization of related components. In this context the SAW duplexer needs special consideration. Recently it has become a key component in the RF front-end of WCDMA wireless phones. Its task is to connect the transmit (Tx) as well as the receive (Rx) branch of a wireless terminal to the common antenna, while ensuring a high isolation level between Tx and Rx pins [1]. The separation between transmit and receive signals is achieved by the assignment of different frequency ranges. Fig. 1 shows a schematic view of the duplexer setup.

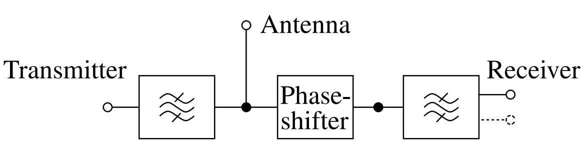
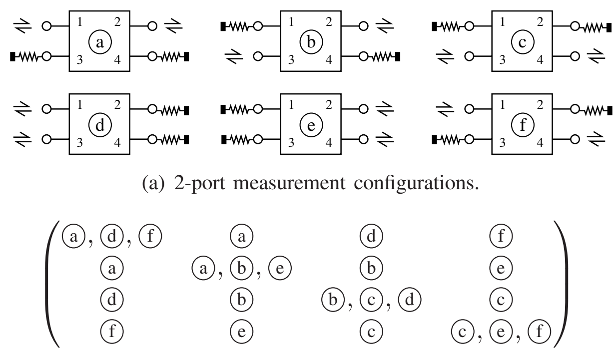


Fig. 1. Schematic view of a duplexer.

It is obvious that a duplexer exhibits at least three ports. Furthermore layouts with a differential Rx output – i.e. with four single-ended ports – are getting more and more popular. Hence, the use of a full 4-port network analyzer is the straightforward method to characterize such a SAW duplexer. Yet, it is also the most expensive approach. Alternatively, the 4-port scattering parameters can be derived from six different 2-port measurements of the device according to Fig. 2(a) [2]. For each configuration a new combination of ports of the device under test is connected to a 2-port network analyzer. The remaining ports are matched to the reference impedance. By the application of this approach all 16 scattering parameters of a duplexer can be determined. The reflection coefficients are measured three times in this procedure and have to be averaged accordingly. The related matrix composition is illustrated in Fig. 2(b).



(a) 2-port measurement configurations.

(b) Allocation of matrix entries.

Fig. 2. Composition of 4-port scattering matrix of 2-port measurement results. The symbols in the matrix indicate the setup in which the respective parameter is measured.

This characterization method is quite time consuming, as a manual reconnection of the device under test is required for each 2-port configuration. The effort can be reduced noticeably by implementing an automatic switching between the necessary configurations [3], [4]. The setup of a realized switching network extension is presented in Section II. The design accounts for the special requirements posed by the device under test – the SAW duplexer. On the one hand very low transmission levels, i.e. the isolation and selectivity of the filters, on the other hand high levels of in-band transmission need to be measured accurately. Hence a high dynamic range of the test equipment and a high isolation level between the test ports are necessary. The operating frequency of the extension ranges from 300 MHz to 6 GHz covering the relevant bands for mobile communication. The presented data are acquired in the range from $45\,\text{MHz}$ to $8\,\text{GHz}$.

In order to compensate for the non-ideal effects of the switching network a calibration is necessary. In Section III a SOLT procedure for the measurement setup is described. Additionally, the influence of non-ideal terminations on the measured duplexer characteristics is examined.

Finally, measurement results for a SAW duplexer are presented in Section IV. They are compared to reference data, which were acquired by a full 4-port network analyzer.

II. Setup

A. Topology

The switching network has to allow for a connection between both ports of the network analyzer (VNA) and at least three different ports of the device under test (DUT). Vice versa every port of the DUT needs to be switchable to at least one port of the network analyzer. The topology shown in Fig. 3 has been chosen for the realized switching network. The displayed switching state corresponds to a measurement of configuration ⓓ in Fig. 2(a).

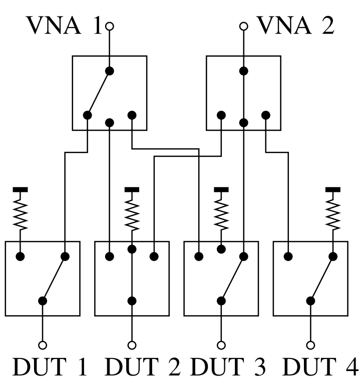


Fig. 3. Topology of the realized switching network.

The two stage design of the extension causes a high inherent isolation level between the network analyzer ports, as every crosstalk path includes at least two open switches. This is advantageous regarding the low transmission levels occuring in a duplexer measurement.

B. Implementation

In order to allow for surface mount technology a microstrip environment has been chosen for the switching network. Integrated PIN diodes are applied as switching elements. They exhibit a high switching repeatibility and are available at low cost for the given frequency range. Biasing is accomplished by SMD elements. A metal housing provides shielding and reduces crosstalk between adjacent lines. A control box is implemented to generate driving currents for the diodes and to allow controlling by a PC via an RS232 interface. The 2-port measurement data are

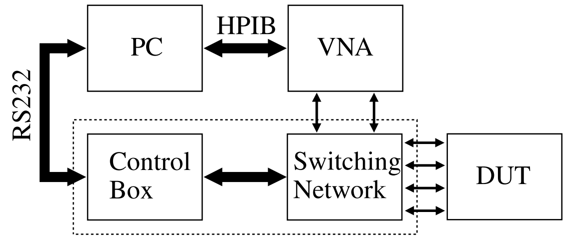


Fig. 4. Block diagram of the measurement setup.

transferred directly from the network analyzer to the PC via an HPIB interface. Fig. 4 shows a schematic view of the measurement setup.

III. Calibration

A. Full 4-Port Calibration

The 4-port extension generates additional attenuation and reflection in the measurement path. The effect of these parasitics is illustrated with a simple measurement example. Without loss of generality, the switching state ⓐ related to Fig. 2(a) is examined assuming a device under test with $|S_{21}| = |S_{12}| = 1$. To uncover the influence of the 4-port extension, the transmission factor of the DUT is transformed to a reference plane at the input of the VNA. Circles for possible values of the transformed scattering parameter S_{21}^{T} are depicted in Fig. 5 for three different frequencies. The marker indicates $\arg(S_{21}) = 0$.

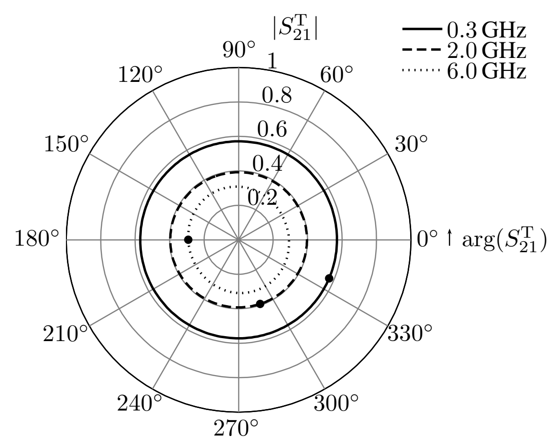


Fig. 5. Measured transmission coefficient S_{21}^{T} for $|S_{21}| = 1$ without correction.

A compression together with a shift of phase values can be noticed. This deformation is frequency dependent and tends to increase with frequency. It can be qualified and compensated for by a calibration, which results in mathematical amplification of the measured scattering parameter. Hence it becomes obvious, that the noise floor and any systematic error in the network analyzer section of the setup are amplified, too. So the dynamic range of the combined test setup is reduced by the non-ideal behaviour of the switching network. A similar analysis can be performed for the reflection coefficients.

Prior to connecting the 4-port extension to the network analyzer, a standard 2-port calibration is accomplished for the VNA itself. Therefore, in the following, this part of the setup can be regarded as ideal. After the connection of both parts, the coaxial lines in between VNA and switching network are fixed and no longer subject to any movement. So a possible systematic error in the VNA section of the setup due to mechanical stress to these lines is minimized. The noise floor of the network analyzer can be reduced by the application of averaging.

To calibrate the 4-port extension, a SOLT procedure for each switching state is performed [5]. Therefore, three reflection standards – i.e. short, open, and load – are required for each port of the extension. Additionally, a thru standard is measured for each switching state. Hence, 18 different connections of standards are necessary in total.

B. Stability of Calibration

In order to evaluate the quality of calibration regarding switching events and time progression, a SAW duplexer has been measured 100 times within 18 hours. Fig. 6 shows exemplarily the result of this measurement series for the transmission from the Tx input (port 1) to the antenna output (port 2). In the upper part of the plot the first measurement of the series is displayed as a reference. In the lower part of the figure the absolute deviation to the reference curve is plotted for all measurements. Within the passband region of the filters a higher density of frequency points has been chosen.

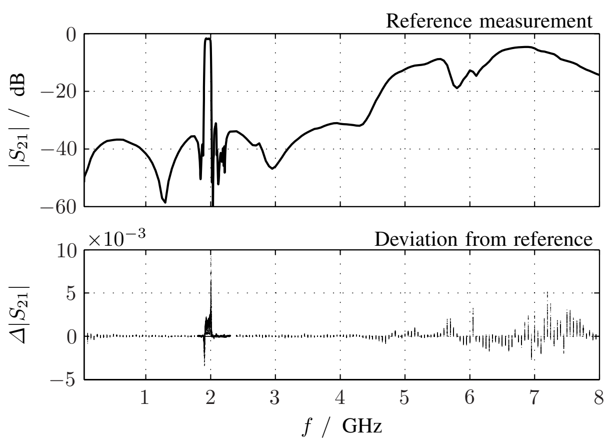


Fig. 6. Measured transmission coefficient $|S_{21}|$. The lower part of the figure shows the absolute deviation from the reference during a series of measurements ($n = 100$). Each measurement is represented by a dot at each frequency point.

The major absolute variation is located at the regions where transmission reaches its maximum. The peaks at the edges of the filter band are due to a small shift in frequency. The values shown correspond to maximum relative deviation of less than $0.025\,\text{dB}$ within the Tx band and less than $0.2\,\text{dB}$ at the remaining frequency points except for transmission zeros. The other transmission parameters show a similar behaviour. For the isolation measurement the relative deviation in the regions above the noise floor and away from transmission zeros is smaller than $0.5\,\text{dB}$. The fluctuations are mainly caused by external effects such as temperature change, which influences the DUT as well as the measurement system. Altogether, the variations determined are within an acceptable range.

In order to reduce the effort for a calibration procedure the feasibility of a simplified approach has been checked. In this case calibration data for the switching network are re-used, assuming a high repeatibility of this part of the measurement setup. Merely the errors within the network analyzer are corrected with a new 2-port calibration, as the combined setup is most sensitive to variations in this section. Comparison between a repeated and the original measurement exhibits a maximum relative deviation in the band region of about $0.1\,\text{dB}$. So this fast approach is applicable, if just a coarse charcterization of a duplexer is needed.

C. Compensation of Non-Ideal Terminations

The composition of 4-port scattering parameters as presented in Section I is based on the assumption of ideal termination impedances. In reality the terminations are not perfectly matched to the reference impedance. If not compensated for, this can cause some distortion in the measured duplexer characteristics.

Below, a 4-port SAW duplexer with balanced Rx output is considered as device under test. A non-zero reflection coefficent $\Gamma \ll 1$ for the terminations is assumed. The following approximation for the error induced by this mismatch on a measured transmission factor S_{ij}^{M} is valid for a characteristic SAW duplexer. Indices i and j denote the ports, which are connected to the network analyzer; t_1 and t_2 reference the terminated ports.

$$\Delta S_{ij}^{\mathrm{M}} \approx S_{it_1} \Gamma S_{t_1 j} + S_{it_2} \Gamma S_{t_2 j} \tag{1}$$

When analyzing (1), main effect of the mismatched ports can be observed at the transmission through the Rx filter in its passband. This is due to the balanced structure of the Rx output. Fig. 7 displays the variation assuming a reflection coefficient $\Gamma = -20\,\text{dB}$ for the terminations. The reference data correspond to a mixed-mode representation of the duplexer. Ports 1 and 2 denote the transmitter and antenna port, respectively, whereas the differential receiver output is refered to as port 3. The relative deviations amount to up to $0.4\,\text{dB}$ for the in-band transmission of the Rx filter. Furthermore, the relative errors at the low levels of in-band isolation between Tx- and Rx-branch and close-by attenuation of the filters are in the range of $1\,\text{dB}$. In summary, the impact of non-ideal terminations at the unconnected ports can reach a considerable level.

To remove the effect of non-ideal terminations, their input reflection factor Γ is measured during the calibration procedure. This can be accomplished while the thru standard is in use. The resulting impedance values are set as reference

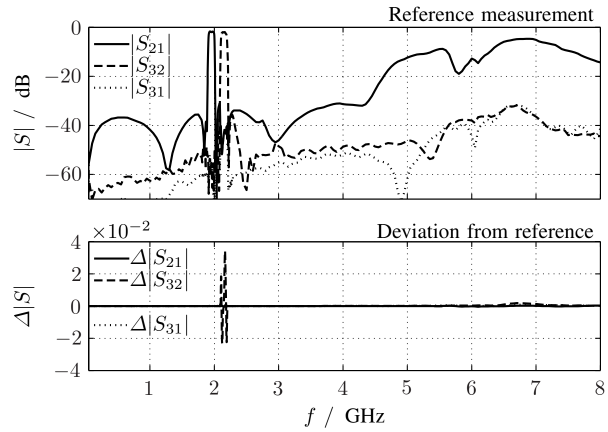


Fig. 7. Comparison of measured transmission factors with ideal (reference) and non-ideal termination impedances ($\Gamma = -20\,\mathrm{dB}$).

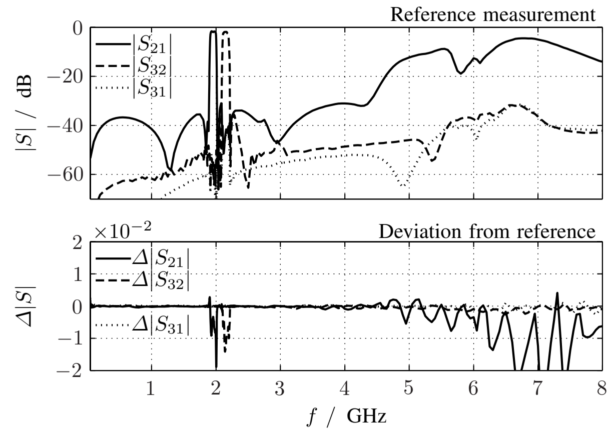
impedance for the corresponding port – i.e. each 2-port measurement result is renormalized to these impedances prior to the composition of the 4-port scattering matrix. Hence, the port impedances are consistent for all entries of this matrix, and the composition is valid. Finally, the resulting scattering matrix is renormalized to $50\,\Omega$ [4].

IV. Measurement Results

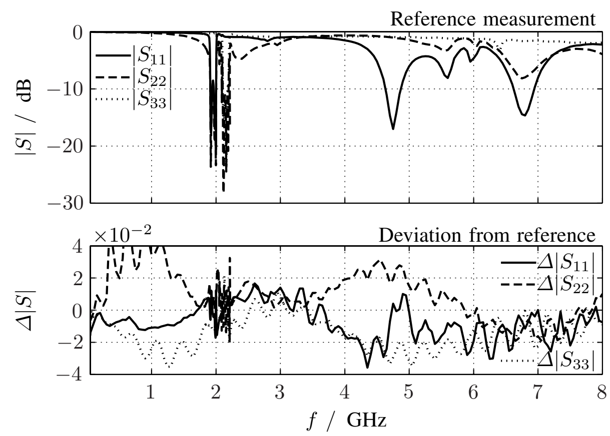
Fig. 8 shows measured transmission and reflection characteristics of a SAW duplexer with a balanced Rx output. Data, which are acquired with the presented 4-port extension, are compared to the results of a measurement with a full 4-port network analyzer. A good match can be observed. Maximum relative deviation in the Tx band transmission factor amounts to $0.1\,\mathrm{dB}$ and in the Rx band transmission factor to $0.15\,\mathrm{dB}$. In this context measurement data acquired with the switching network extension is superior to the results of a manually reconnected DUT. In the second case connection cables are bent in different way for each configuration. Hence a systematic error is introduced, which in this example has its main influence at the Rx transmission band. The shape of the corresponding scattering parameter would be altered and the maximum relative deviation would even amount to $0.3\,\mathrm{dB}$.

V. Conclusion

A switching network has been presented, which extends a 2-port network analyzer for 4-port measurements. In this context the characteristics related to the measurement of a SAW duplexer with a 2-port network analyzer are treated. Finally, the functionality of the chosen appoach has been proved by comparison of measurement results to data acquired with a full 4-port network analyzer.



(a) Transmission coefficients.



(b) Reflection coefficients.

Fig. 8. Measurement results for a SAW duplexer acquired with the 4-port extension compared to reference data.

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