An Efficient and Cost Effective SAW Device Measurement Method Based on an S-Parameter Estimation Technique

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ABSTRACT

Efficient and cost effective testing is an important part of the production process of SAW components. One aspect of testing is the measurement of the device transfer characteristic. In many cases expensive test fixtures containing matching networks are required. In order to reduce production costs and facilitate the measurement of transfer functions without matching networks, a different approach has been taken. Through use of estimation methods one can reduce the amount of information required to calculate a matched transfer function. Therefore, we developed a method by which a simulated match could be performed, but required only knowledge of the unmatched and uncalibrated S_{21}-parameter. The feasibility of our technique is demonstrated with a low loss IF SPUDT filter for mobile telephone applications.

INTRODUCTION

Since a network analyzer is usually set up for a 50Ω environment, a device whose input/output impedances are not close to 50Ω must be measured using matching networks. Normally several test fixtures which include the matching networks are prefabricated for each device type that will go into production. Since several test fixtures may be in use or exchanged during production, it is necessary that they be as precisely fabricated as possible. One then is in a position to obtain comparable results, regardless of which test fixtures are used. It is easily observed that the testing of an entire line of devices results in a considerable expense in costly test fixtures. Since no two test fixtures can be exactly reproduced, a certain extra tolerance must be allowed for when testing.

One way to circumvent these problems and also reduce costs is to make unmatched measurements and then perform the match using a computer algorithm. If one has knowledge of the complete S-matrix of the DUT and of the matching networks, a simulated match is easily performed. In order to employ this method, one must first perform a full two-port calibration of the network analyzer. During testing, this method is slower since two sweeps must be made. This is in contrast to the normal method where only one sweep is required. The standard method would consist of a setup using hardware matching networks and a network analyzer that is only thru- calibrated. In a production environment, accuracy, measurement time, simplicity of calibration, and cost effectiveness are of primary importance. Therefore, our goal was to find a method by which a simulated match could also be performed, but required only knowledge of the S_{21}-parameter measured without matching networks or calibration.

IMPLEMENTATION

Several problems with this method must first be overcome. First, one must somehow eliminate noise errors in the measurements. This can be accomplished by smoothing the data. A third order, five point smoothing could be carried out using the following formula,

$$\bar{y}_n = \frac{1}{35}\cdot\left(-3y_{n-2} + 12y_{n-1} + 17y_n + 12y_{n+1} - 3y_{n+2}\right), \quad (1)$$

where n refers to sample points within a spectrum measurement. Optimal smoothing techniques can be found in [1]. Second, any frequency drifts and/or phase shifts between individual measurements should be accounted for. By removing any drifts, one can improve the estimation step. Afterwards the drift can be replaced to reflect the true measurement. Third, an adequate model of the input/output matching networks must be realized, or an S-matrix measurement of the hardware realization must be available. Fourth, test fixture effects should be accounted for. Finally, the unmatched and uncalibrated parameters S_{11} and S_{22} of a given DUT must, by some other method than measurement, be obtained. The SAW components to be so measured, e.g.

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low loss filters, are reciprocal. Thus, forward and reverse transmission coefficients are equal. Obtaining S_{11} and S_{22} is the central problem. This lack of information can be overcome by estimation or prediction methods. Once the complete S-matrix has been gained, the matched frequency characteristic including a full two-port calibration may be calculated.

ESTIMATION

The estimation procedure used relies on the fact that there is a correlation between S_{21}, S_{11}, and S_{22} for many SAW devices. As an example, Figure 1 demonstrates the relationship between S_{11} and S_{21} for 100 representative measurement samples of a commercial low loss single phase unidirectional transducer (SPUDT) SAW IF filter.

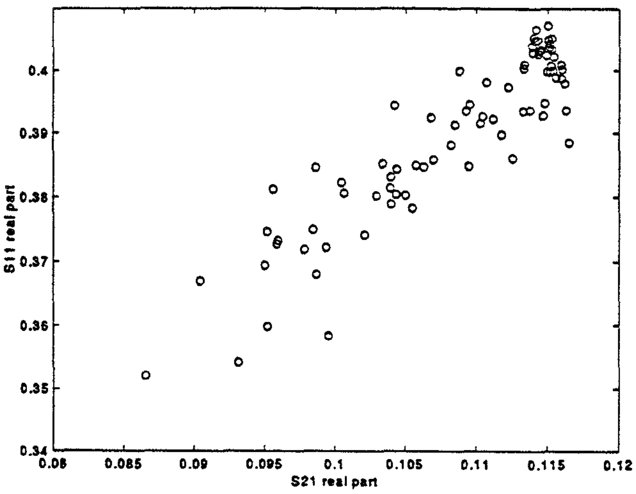

Fig. 1a: Correlation between S_{11} and S_{21} at the center frequency (real part).

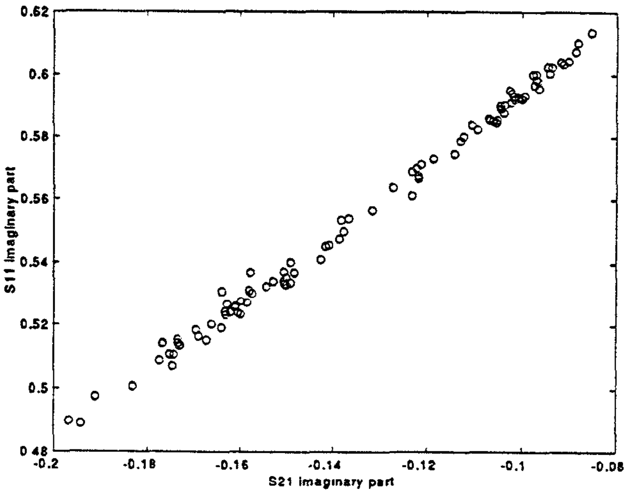

Fig. 1b: Correlation between S_{11} and S_{21} at the center frequency (imaginary part).

An optimal estimator for S_{11} and S_{22}, if there is a most efficient estimator at all, can be found by the maximum likelihood method. Since the measurement errors are nearly normally distributed and statistically independent, the maximum likelihood problem can be restated as a linear least squares or mean square estimation problem [1]. Up to third order dependencies can be found by solving the following matrix equation:

$$\begin{bmatrix} N & \sum x_n & \sum x_n^2 & \sum x_n^3 \\ \sum x_n & \sum x_n^2 & \sum x_n^3 & \sum x_n^4 \\ \sum x_n^2 & \sum x_n^3 & \sum x_n^4 & \sum x_n^5 \\ \sum x_n^3 & \sum x_n^4 & \sum x_n^5 & \sum x_n^6 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} = \begin{bmatrix} \sum y_n \\ \sum x_n y_n \\ \sum x_n^2 y_n \\ \sum x_n^3 y_n \end{bmatrix} \quad (2)$$

where the sums are over the N measurements used to determine the correlation. Solving for the coefficients yields a polynomial describing the statistical relationship between x and y:

$$y = \alpha_1 + \alpha_2 x + \alpha_3 x^2 + \alpha_4 x^3 \quad (3)$$

For higher order functions, splines would be used to avoid any unwanted oscillation between the data points. Substituting S_{21} for x and S_{11}/S_{22} for y in eq. (2), we obtain the required coefficients. Eq. (2) must be solved for each frequency point. These coefficients would then be stored in a database. During subsequent testing only eq. (3) together with the above coefficients would be required.

We therefore obtain best estimates through the use of regression curves describing the statistical dependencies among the individual S-parameters. These may be linear or nonlinear, depending on the type of DUT under consideration. If we have determined the necessary regression curves, we may estimate S_{11} or S_{22} from a knowledge of S_{21} alone. Further, if one eliminates the frequency drifts in the individual measurements, the correlation between S_{21} and S_{11}/S_{22} can be further strengthened. In the examples shown below, no frequency drifts were compensated for. In a practical application, one would maintain a database containing the required regression curves, calibration terms, and the test fixture characterization for each type of device. Then, during the testing process only S_{21} is measured in an unmatched test fixture. After estimation of the other S-parameters, using eq. (3), a match is computed. In order to obtain valid regression curves many measurements are required for each type of device. In Figure 2, a comparison of true and estimated unmatched S_{22}-parameters is shown. The dashed curve is measurement, the full curve is estimated. The estimation is based on 100 representative S-matrix measurements.

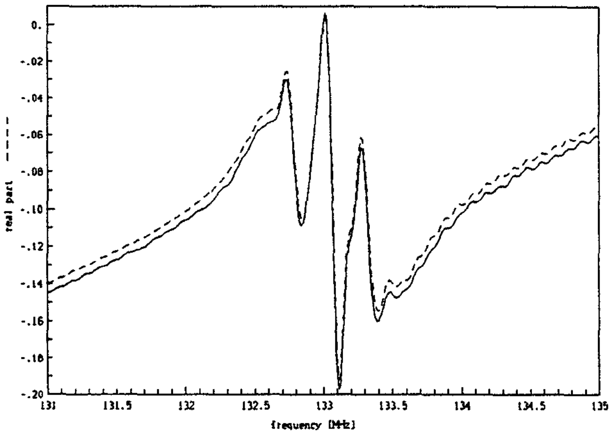

Fig. 2a: Comparison of true and estimated unmatched S_{22}-parameters (real part).

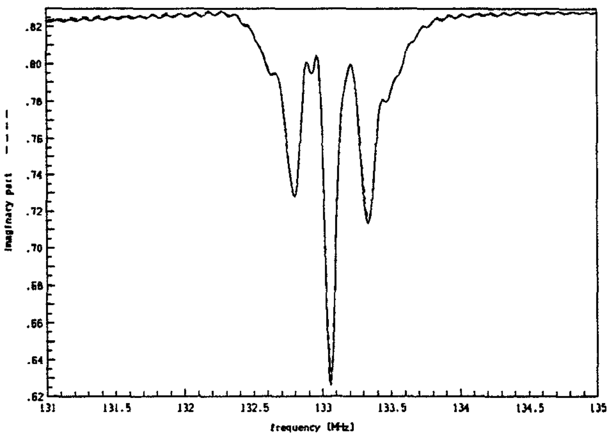

Fig. 2b: Comparison of true and estimated unmatched S_{22}-parameters (imaginary part).

A further improvement in accuracy is possible at the expense of an increase in a-priori measurement data, although this only needs to be done once. Selection of representative measurements is important, as different wafers may have slightly shifted distributions. One should try to gain samples over the whole distribution of wafers. Clearly, this method is only practical for larger series of measurements, as is the case in production.

TEST FIXTURE CHARACTERIZATION

In Figure 3, a real test fixture with hardware matching networks has been modeled using ideal bulk elements, allowing the DUT's behavior in a real circuit to be very closely simulated.

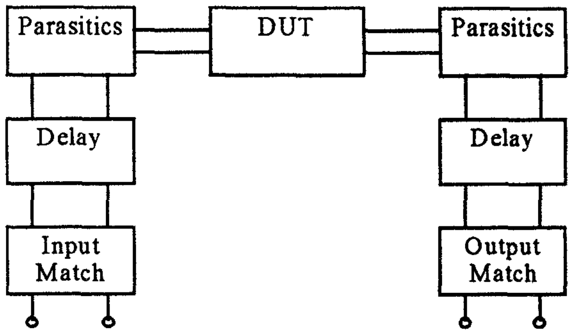

Fig. 3: Test fixture characterization

The errors introduced here due to an inadequate model are very small. The matching networks for the examples shown here were modeled by using a seriell inductance, and a parallel capacitance. The inductance and capacitance values are specified by the SAW design. Ohmic losses in the matching networks are accounted for by specifying the Q-values for the individual matching elements. The parasitic networks consist of stray inductances/capacitances including ohmic loss. These elements as well as the delay lines must be determined either experimentally or by optimization. The optimal values were found by constrained optimization of the DUT's matched insertion loss (simulation), where the contraints were placed on passband ripple and stopband attenuation level. The optimization routine implemented is the nonlinear quadratic optimization described by Kuhn-Tucker.

PROCEDURE

Once the regression curves, calibration terms, and test fixture characterization are available, a full two-port calibrated match can be calculated from a knowledge of S_{21}, measured unmatched and without calibration. The individual networks are cascaded using eq.'s (4), which allow cascading of three matrices.

$$
\begin{aligned}
D\cdot S^R_{11} &= S^1_{11}(1 - S^2_{22}S^3_{11}) - \det \mathbf{S}^1 (S^2_{11} - S^3_{11}\det \mathbf{S}^2)\\
D\cdot S^R_{12} &= S^1_{12}S^2_{12}S^3_{12}\\
D\cdot S^R_{21} &= S^1_{21}S^2_{21}S^3_{21}\\
D\cdot S^R_{22} &= S^3_{22}(1 - S^1_{22}S^2_{11}) - \det \mathbf{S}^3 (S^2_{22} - S^1_{22}\det \mathbf{S}^2)
\end{aligned}
\qquad (4)
$$

where $D = 1 - S^1_{22}S^2_{11} - S^3_{11}\left(S^2_{22} - S^1_{22}\cdot \det \mathbf{S}^2\right)$,

and the superscripts 1,2 and 3 refer to the left, middle, and right matrices which are to be cascaded, respectively. The superscript R refers to the result. The flow chart in Figure 4 shows an overview of the procedure.

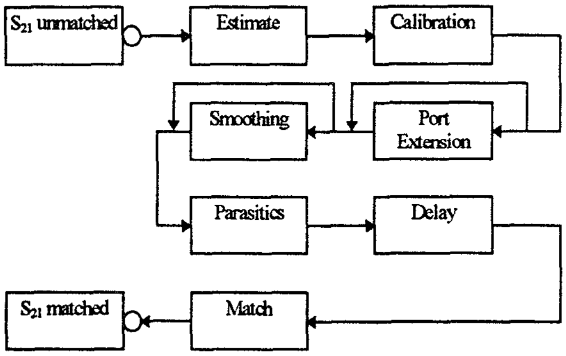

Fig. 4: Procedural overview

EXPERIMENTAL RESULTS

The following example demonstrates the feasibility of the estimation method with a commercial low loss SPUDT SAW filter for the intermediate frequency (IF) band of the mobile telephone system GSM. Center frequency, 3 dB bandwidth, and group delay are 133.0 MHz, 150 kHz, and 1 μs, respectively. The passband ripple is less than 1 dB. In Figure 5, a comparison of measured and estimated transfer functions is shown.

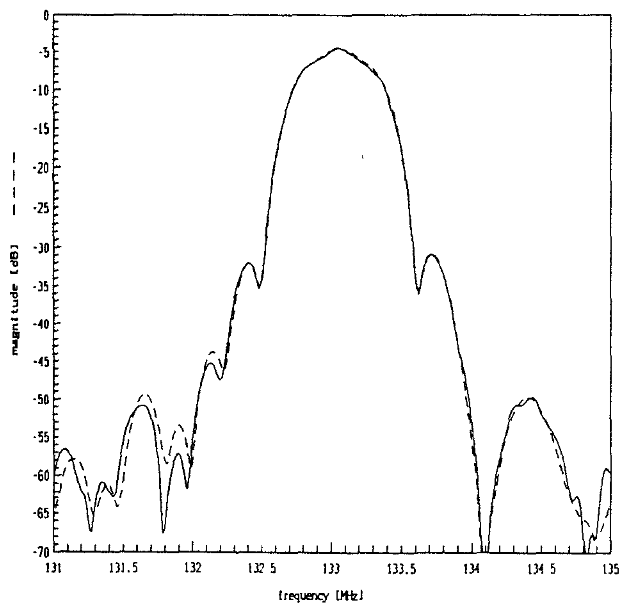

Fig. 5a: Comparison of S_{21} transfer functions. The dashed curve shows the true transfer function. The full curve shows the simulated transfer function.

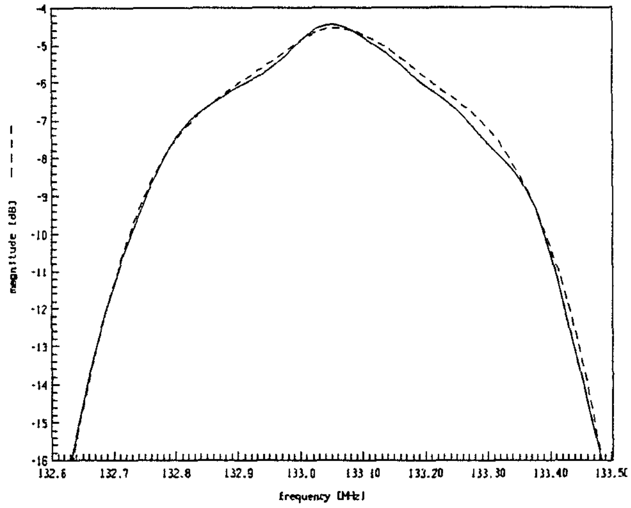

Fig. 5b: Passband comparison of same low loss filter.

CONCLUSION

Due to the high quality of the estimation, results have been achieved with a total error less than 0.25 dB in the passband. In the stopband similar results have been obtained. The errors introduced by the estimation can be further reduced by applying more a-priori measurement data. Refining the test fixture model may be required at much higher frequencies, or very large bandwidths. Further advantages may be offered by using Kalman filtering.

ACKNOWLEDGEMENTS

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REFERENCE

[1] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, New York: McGraw-Hill, 1991.