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Simple Matching Strategy for Surface Acoustic Wave (SAW) Delay Lines in Radio Frequency (RF) Applications

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Abstract- To achieve best performance in radio frequency (RF) circuits it is necessary to match each active component to the characteristic system impedance. This requirement is also valid for passive surface acoustic wave (SAW) filters and, as used in this application, delay line elements. Matching circuits are commonly built up by inductors and capacitors, arranged as L-type, PI-type or tee-type network. In addition to component losses also the layer setup of the printed circuit board (PCB) and also the routed traces influence the overall performance of the system. Nowadays several free matching tool software programs available in the internet help to calculate the matching network at a given frequency for a desired complex load, but nevertheless also other edge conditions have to be taken into account. This paper shows how it is possible to achieve the best matching result for the given delay line element and also how real components influence different parameters like the group delay, the insert losses and the pass band ripple. Briefly also the advantages and disadvantages of the L-structured matching network are discussed and simple rules are presented to reduce the number of design iterations.

Keywords- *Surface Acoustic Wave, SAW, RF Matching Network; QUCS; Group Delay Simulation, Delay Line, Matching Strategy, Passive Matching Network, Matching Network Calculation.*

I. INTRODUCTION

The surface acoustic wave (SAW) sensor element represents a delay line, which is built up by two separated inter-digital transducers (IDTs) with a defined distance to each other; refer to Fig. 1, [1].

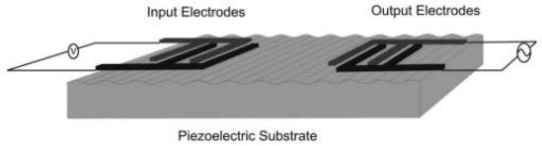

Figure 1. Delay line structure, where two sets of electrodes are patterned on the surface of the piezoelectric substrate. The electrodes are arranged in an inter-digital pattern.

If a signal is applied to one of the IDT the wave takes some time to reach the other receiving IDT, which is exactly related to the kind of wave and also the substrate material characteristic that shows a defined propagation velocity. The phenomenon of SAW propagation was first reported on by Lord Rayleigh in 1885, [2]. But it took some time until 1965 that such wave motion, which is known as Rayleigh waves, could be used efficiently for filters and other electronic applications, when it was possible to metalize such IDTs on a piezoelectric substrate, [3]. The IDT is just a two finger comb structure that can be mass produced by using photolithography, which has been well developed for semiconductor device fabrication. One finger is supplied with the signal and the other one is connected to ground potential. This structure leads to build up a capacitive structure, which must be matched externally. The input impedance and the unmatched frequency response are shown in Fig. 2 as S11 and Fig. 3 as S21 in a 50 Ω system.

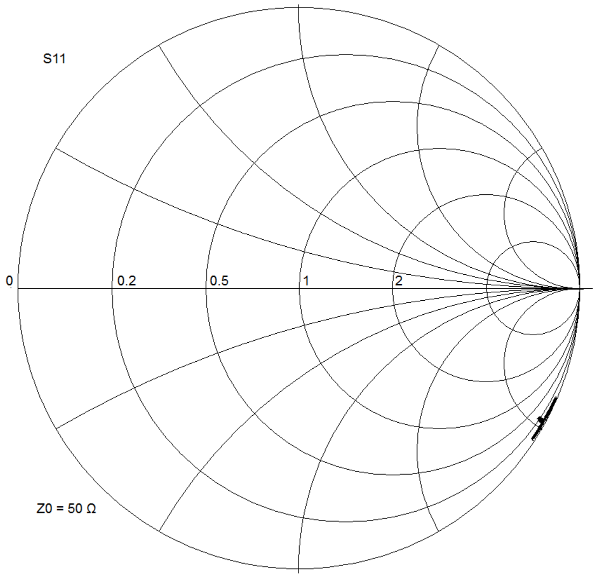

Figure 2. Measurement of the S11-parameter of the used unmatched SAW delay line element.

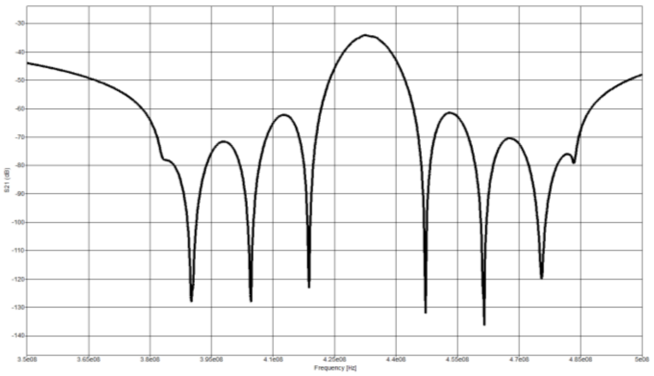

Figure 3. Measurement of the S21-parameter of the used unmatched SAW delay line element.

The rejection from the main center response to the spurious side lobes is approximately 30 dB. The bandwidth, pass band amplitude ripple and phase linearity are highly dependent on the interaction between the SAW delay line and the impedance presented to it, represented by the source and load and the matching network coupling to the source and load.

If it is wished to extract maximal power from the source it is necessary that on each link to the load a conjugate complex matching is available. This employs a matching network between the RF source and the load. Routing traces with very few losses at the matching do also have small additional losses caused by standing waves, if a defined voltage standing wave ratio (VSWR) is not exceeded. The ratio of the given load impedance of the inter-digital transducer structure to the intrinsic impedance defines the VSWR on the trace. The matching network consists of inductors and capacitors, where the ohmic losses of the inductors are especially problematic because the quality factor can rarely achieve values greater than 100. Each high frequency source has a given power, but dependent on the matching only a part of it is available at the load. The rate of matching can mathematically be described by the reflectance coefficient where at perfect matching the supplied power is transferred to the real part of the load.

Another important factor is the group delay time τ_{gr} that is defined as negative derivation of the phase response φ of the measurement unit over the frequency *f*,

$$\tau_{\mathrm{gr}} = -\frac{1}{360°} \cdot \frac{\mathrm{d}\varphi}{\mathrm{d}f}. \tag{1}$$

A vector network analyzer measures the phase of the transfer parameter S21 of two adjacent frequencies sequentially and calculates instead of the derivation the differential quotient of the phase,

$$\tau_{gr} = -\frac{1}{360°} \cdot \frac{\Delta\varphi}{\Delta f}. \tag{2}$$

This leads to a proper approximation for the group delay time, as long as the change in phase can be expected to be linear within the frequency interval Δf, which is also named as frequency aperture shown in Fig. 4, [4]. This kind of phase measurement based on the S-parameters is extremely precise, because of the fact that the measurement accuracy of the network analyzer can be increased by proper calibration. So it is perfectly suitable for measurement objects like amplifiers or passive components, like in this case filter or delay line elements.

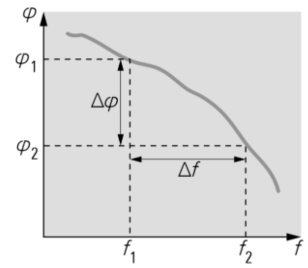

Figure 4. Frequency aperture with the terms $\Delta\varphi = \varphi_1 - \varphi_2$ and $\Delta f = f_1 - f_2$.

For this investigation the simulation tool QUCS, [5] was used to calculate the group delay time. The result of the unmatched SAW delay line element is shown in Fig. 5. To calculate the group delay the formula (2) has to be implemented in the equation block of the simulation tool. The following equation (3) has to be implemented in the editor,

group_delay=diff(rad2deg(unwrap(angle(S[2,1]))),

frequency)/360(-1)* (3)

The result of the computation is shown in Fig.5. The SAW element cannot be used in an application that demands very high accuracy, without any matching circuit because the group delay is not stable over the pass band.

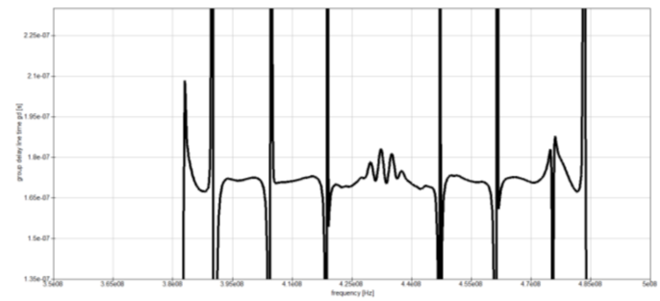

Figure 5. Calculation of the group delay time of the unmatched SAW delay line element.

II. Matching Network Development

Especially if using passive SAW filters a conjugate matching between the source impedance of a driver and the impedance of the connected load is desirable, to minimize signal coupling losses by maximizing the power transfer. In this particular case, if using a delay line element as defined load, the impedance can be described by,

$$\mathrm{Z_L} = \mathrm{R_L} + \mathrm{j} \cdot \mathrm{X_L} \tag{4}$$

Where R_L and X_L respectively symbolize the resistive and reactive components. Assuming that the source impedance is described by a real part R_S and reactive component X_S, the maximum power transfer mandates if $R_S = R_L$ and $X_S = X_L$ at a desired frequency or over a required frequency pass band, [6]. Because these criteria are not satisfied automatically, a compensation network must be incorporated between the source and the load. An obvious companion requirement of the inserted matching circuit is that it effects the impedance transformation without incurring significant power loss between its input and output ports.

The design strategy for the impedance matching network for the SAW delay line is that first of all the impedance value at the center frequency f_c of the pass band is taken, and calculated from the measured S-parameters. Therefore the cursor is set to the point of interest and with equation (5) the complex device impedance Z_L is calculated.

$$\underline{Z_L} = \frac{1+S_{11}}{1-S_{11}} \cdot Z_0 = R_L + j \cdot X_L \tag{5}$$

Referring to Fig. 2 the element consists of a small real part R_L and a high capacitive imaginary part X_L. The source impedance with the characteristic 50 Ω shows a higher resistance than the sensor element so the matching network arrangement as L-structure, shown in Fig. 6 must be used.

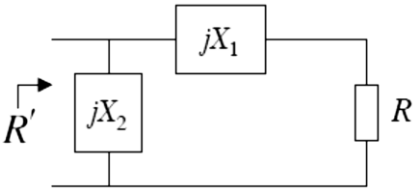

Figure 6. Component arrangement of the L-structure matching network.

In the next step the load reactance X_L resonates at the frequency of interest if an equal and opposite reactance X_1 is inserted in the longitudinal branch of the matching network, yielding to,

$$X_1 = X_L{}^* \tag{6}$$

With this very simple calculation, the value L of the length element, which is an inductor in this particular case, can be computed - assuming that it is dealt with ideal components.

$$L = \frac{X_1}{2 \cdot \pi \cdot f_c} \tag{7}$$

Now the loaded system quality factor Q can be calculated (8), if assuming that the quality factor of the inductor itself is very high or even endless in the case of an ideal element that is the base of this investigation.

Further on the parallel reactance X_2 and out of this the value of the capacitor can be computed by (9, 10), leading to the entire matching circuit shown in Fig. 7.

$$Q = \frac{X_1}{R_L} \tag{8}$$

$$j \cdot X_2 = -j \cdot X_1 \cdot \left(1 + \frac{1}{Q^2}\right) \tag{9}$$

$$C = \frac{1}{X_2 \cdot 2 \cdot \pi \cdot f_c} \tag{10}$$

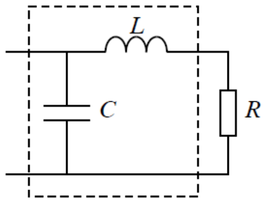

Figure 7. Passive L-structured matching network to connect the delay line SAW element.

At this point the optimal matching circuit is found but just if using ideal elements. Next the network is implemented in the simulation tool and additionally also real measurement data of real inductors are used to show the difference between the ideal and real world and also to tune the values to achieve best results.

III. VERIFICATION WITH THE SIMULATION TOOL

The SAW sensor with its matching network is implemented into the simulation tool and the result is shown in Fig. 8 and Fig. 9 for its insertion loss S11, Fig. 10 for the transfer function described by S21 and Fig. 11 shows the achieved group delay time compared to the unmatched device. It is important to notice, that especially inductors show different physical effects if using them in RF applications, [7]. With increasing frequency the inductivity value and also the quality factor rises. In this particular case of the used delay line element the inductor should have a value of about 72 nH and the capacitor a value of approximately 1.9 pF. If standard values are taken, the nearest inductivity value is 68 nH. Because of the increasing value with increasing frequency the next lower one is taken. Best performance is also achieved, if the quality factor of the component is very high. Additionally it has to be considered that the SAW sensor element is connected with bond wires, that also shows additionally inductance so that the required 72 nH are quite well achievable. Also the capacitance value offers some place to play with. If the S-parameter measurement file is implemented into the simulation tool the best value for the capacitor can be determined. Of course the result of the simulation tool must be verified with measurements taken on the PCB, to consider the routed traces and every other parasitic effect. For the practical implementation an inductor of the Johanson Technology Inc. of the type 07C68N was used and for the capacitors ideal components were taken, caused by their nearly ideal properties at the used frequency around 433 MHz. In this particular case a capacitor value of 3.3 pF is best choice to achieve minimal ripple in the group delay time over the bandwidth, by acceptable insertion loss and a good transfer function.

The advantage of this simple matching network design method is that it has very low cost caused by the few necessary components, it is simple in the setup with minimal routing afford and easy to design. The disadvantage is that neither the overall quality factor nor the bandwidth is controllable and therefore it is just useful to take this type of matching just for narrow bandwidth and low cost applications.

The following figures show the simulation results of the realized matching network, once with ideal components and once with real parts.

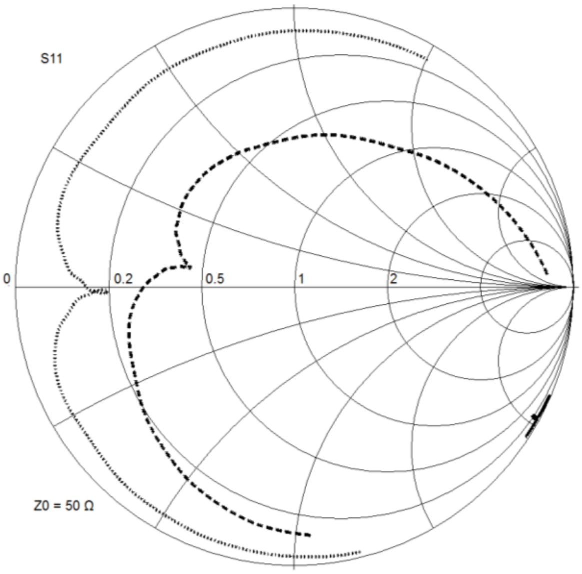

Figure 8. Comparision of the simulation result of S11 between the unmatched (solid line) SAW device, the matching network with ideal components (dotted line) and the matching network with real components (dashed line).

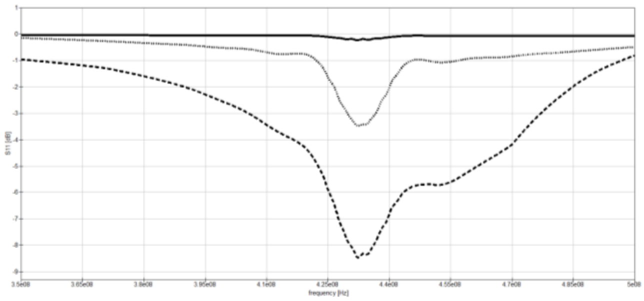

Figure 9. Simulation result of S11 in [dB] between the unmatched (solid line) SAW device, the matching network with ideal components (dotted line) and the matching network with real components (dashed line).

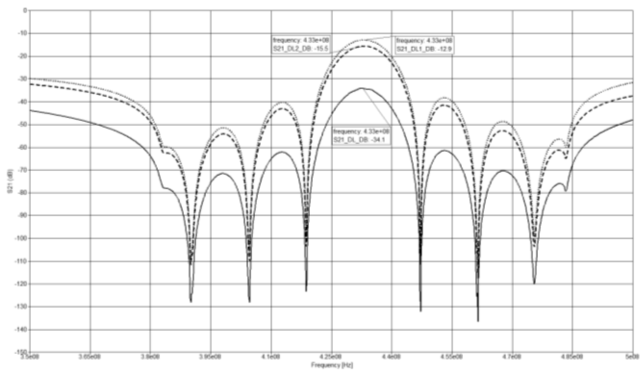

Figure 10. Comparision of the simulation result of the transfer function S21 between the unmatched (solid line) SAW device, the matching network with ideal components (dotted line) and the matching network with real components (dashed line).

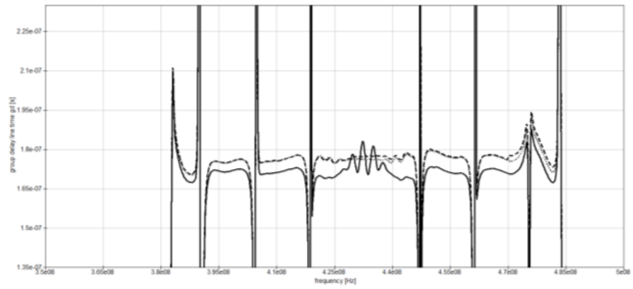

Figure 11. Simulation result of the group delay time of the unmatched (solid line) SAW device, the matching network with ideal components (dotted line) and the matching network with real components (dashed line).

IV. SUMMARY

In this paper a simple approach to develop an L- structured matching network is presented. It is shown that it is not enough just to calculate the values for the components, but it is also necessary to consider physical effects that appear at high frequencies for example in real inductors. The following Tab. 1 points out the achieved results. With very few equations it is possible to easily design an adequate L-structured matching network for SAW delay lines for quite narrow bandwidth and low cost applications.

TABLE I. SIMULATION RESULTS OF THE PARAMETERS AND THE MATCHING NETWORKS WITH IDEAL AND REAL COMPONENTS.

	S11 [dB]	**S22 [dB]**	**$\tau_{gr\ min}$ [ns]**	**$\tau_{gr\ max}$ [ns]**
SAW Sensor	-0.23	-34.1	169	183
ideal match	-3.47	-12.9	175	176
real match	-8.45	-15.5	175	177

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