Towards Improved Manufacturing Yield of Acoustic-Wave Ladder-Type Filters

Mohammad J. Almalkawi
Skyworks Solutions, Inc., Greensboro, NC 27409, USA
Mohammad.Almalkawi@skyworksinc.com

***Abstract*—Monte Carlo (MC) analysis and yield optimization methods are often used to describe the manufacturing process variability as a means to estimate production yield in various disciplines of semiconductor industry, however are not quite employed or fall into disuse at the design and development phases of acoustic-wave (AW) filters and multiplexers. In this study, MC yield analysis approach is exploited as a design centering method to obtain high yield estimate. An illustrative example of Band 41 surface acoustic-wave (SAW) ladder-type filter is utilized to demonstrate the advantages of the presented approach.**

***Index Terms*—Acoustic-wave, bandpass filter, ladder topology, Monte Carlo analysis, yield optimization, sensitivity.**

I. INTRODUCTION

Design for manufacturability (DFM) and design for testability (DFT) are two important design practices that stress the need for careful attention at the early design stages of a product in order to meet a given set of design specifications while reducing the complexities involved in manufacturing and testing. Overlooking critical design aspects can adversely influence the product time-to-market and the number of re-design cycles needed for high production yield. In this context, proactive steps during the design phase that can bridge the gap between the experimental and the analytical expectations and offer a high degree of insight into the design critical components are highly desirable.

This paper therefore extends the use of Monte Carlo (MC) analysis and yield optimization to the design phase of acoustic-wave (AW) ladder-type filters. A ladder topology has been the most widely used configuration in AW filters comprising high performance crystal resonators. This can be attributed to the low sensitivity of ladder networks if compared to its counterparts of lattice topologies. In fact, a lossless reciprocal two-port doubly-terminated ladder network possesses minimal sensitivity to its component variations other than the termination elements at frequencies where the transducer power gain, $|S_{21}|^2$, is unity over the passband [1, 2]. Whereas a lattice topology requires a balanced condition between its bridged impedance branches in order to realize a transmission zero by having identical and precise component values [3]. Moreover, sensitivity of the components forming a high selective ladder filter network is minimal when the input and output termination impedances are identical. Having an impedance transformation ratio other than one or frequency-dependent terminations will affect the sensitivity properties of the network. This can be encountered in cases where a filter is integrated in an RF transceiver module that necessitates a specific interface immittance at the input and output terminals of the filter, other than 50 ohms. This is to accommodate, for example, carrier aggregation requirements in a multiplexer configuration, and/or interface impedances at the output of a power amplifier or at the input of a low-noise amplifier. In addition to the influence imposed by the impedance transformation ratio on the sensitivity of a ladder network, incorporating external passive components adds another degree of implication due to their manufacturing tolerances. Externally added inductors are key components in AW ladder filters and are utilized for impedance matching, extending the bandwidth or placing transmission zeros. Such inductors are usually realized as surface mount devices (SMDs) or as embedded inductors in a multilayer laminate.

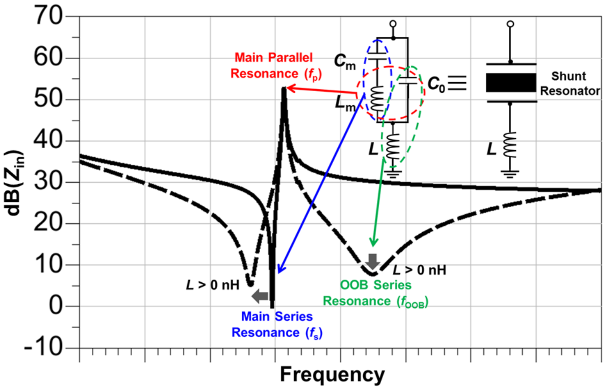

Fig. 1. Impedance response over frequency of an AW resonator without external components (solid line) and with an external lumped inductor (L) cascaded in series (dashed line). Circuit schematic of the lossless BVD model illustrates the key components that contribute to each of the highlighted resonance frequencies.

The objective of this study is to extend the capabilities of MC statistical analysis in simple terms as a design centering method to the external components added to an AW filter so that better yield and less sensitive design is obtained. Among the several tolerance analysis techniques, MC is a comprehensive approach that provides cost effective statistical models capable of predicting failures/sensitivities of the model parameters by conducting reduced number of experiments to cover the design space. Moreover, the accuracy of the analysis is independent of the number of the design variables. This makes MC analysis more convenient for analyzing large RF modules as it is impractical to cover all possible scenarios of the design parameters via closed form mathematical methods.

II. ATTENUATION IN AW LADDER FILTERS

The stringent requirements for modern communication systems impose a large number of rejection specs on the filter's response. As a result, most of yield loss occurs due to not meeting the rejection requirements if compared to not meeting the filter's bandwidth, matching or insertion loss (IL) specs.

It is well-known from the Butterworth-Van Dyke (BVD) model [4] that the out-of-band (OOB) impedance characteristic of an AW resonator and an AW-filter as a consequence is capacitive. Intuitively, for a signal to reach from the input to the output of a ladder filter network with minimal loss requires low impedance and high impedance in the series and shunt branches, respectively, within the in-band frequencies. In a sense, increasing the series to shunt capacitance ratio improves the passband matching at the expense of the overall attenuation floor of the filter at the OOB frequencies and vice versa. This inseparable fact makes achieving high rejection at the OOB of a bandpass filter (BPF) while maintaining low IL in the in-band quite challenging.

A. OOB Attenuation Far from the Passband

An AW ladder filter comprises series and shunt resonators/branches with each possesses a finite capacitance at the OOB frequencies. This implies that series resonators are the main contributor to the attenuation level at the very low OOB frequencies, while shunt resonators have strong influence on the attenuation level at the very high OOB frequencies.

B. OOB Attenuation Close to the Passband

AW BPFs used in mobile communication systems require high levels of attenuation in the proximate and contiguous bands. This is to ensure low susceptibility to potential power leakage from nearby transmitting bands; a fact that is crucial in the design of manifold multiplexers where rejections from one filter into others are inevitable to meet the system-level performance requirements. Therefore, a filter solution will possibly have an asymmetric frequency characteristic with high rejection level at one side of the passband and relatively poorer attenuation at the other side.

Fig. 1 shows a schematic of an AW resonator where L_m and C_m are the motional inductance and capacitance, respectively. C_0 is the static capacitance of the resonator and L is an external lumped inductor usually added in series to a shunt resonator for generating a band-notch at the lower and/or upper side of the filter's passband. Controlling the band-notch location at the upper side of the passband, however, is more challenging as it relies considerably on the parasitic electromagnetic (EM) environment surrounding the filter's network.

III. MONTE CARLO YIELD ANALYSIS AND OPTIMIZATION

MC analysis is a set of statistical algorithms based on non-deterministic probabilistic methods that involve randomly sampling the design input space around their nominal values with specified probability distribution functions so that development of statistical models can be obtained and accurate estimate of the statistical characteristics representing the entire population is achieved. Pass and fail criteria of each sample is determined by a set of predefined design specifications where all samples are evaluated and recorded to estimate the total yield or yield per each design variable. To this end, histograms can be formed to display the recorded data resulted after performing the yield analysis at each of the different design input parameters. Based on the initial yield data, yield optimization is carried out by adjusting the nominal values of each variable so that it maximizes the yield estimate.

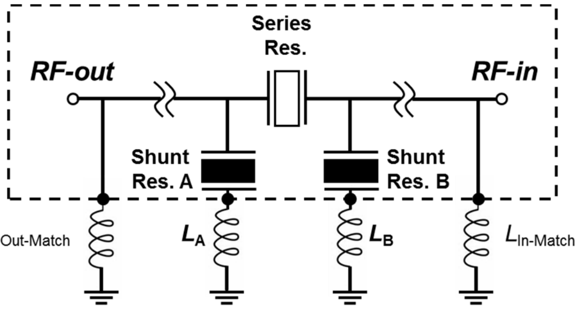

Fig. 2. A ladder topology of a BPF comprises series and shunt AW resonators. Shunt resonators are cascaded with series inductors (L_A and L_B) in order to place OOB transmission zeros. Shunt inductors ($L_{\text{Out-Match}}$ and $L_{\text{In-Match}}$) at the input and output terminals of the filter are used for impedance matching.

The variability or dispersion of an added circuitry component can be simply expressed by defining a range which indicates the difference between the extreme values, a variance which is calculated by averaging the squared differences of all the values from the mean or nominal values, or standard deviation (σ) which is the square root of the variance. Worst-case analysis achieved by varying the design parameter values to their extremes in a way that produces the worst possible results is referred to as corner simulations. Using MC interpolation schemes to interpolate between the design corners and the nominal design is possible by adaptively and randomly sampling the design space in order to provide statistical models either in the form of probability density function (PDF) or cumulative distribution function (CDF).

Among the several random sampling techniques that can be combined with MC analysis, pseudo-random sampling (PRS) is one of the convenient methods that can repeatedly produce random samples in a deterministic fashion from a particular probability distribution [5]. Compared to a truly random sampling generator, PRS ensures reproducibility of the generated samples so that results obtained by performing MC simulations at multiple times are comparable. Normal (Gaussian) distribution is usually used to characterize uncertainty associated with the design component tolerances. According to the *central limit theorem* (CLT) in probability [6]: the properties of a sufficiently large number of samples of an independent random variable tend toward a normal distribution regardless of the distribution from which they are sampled from.

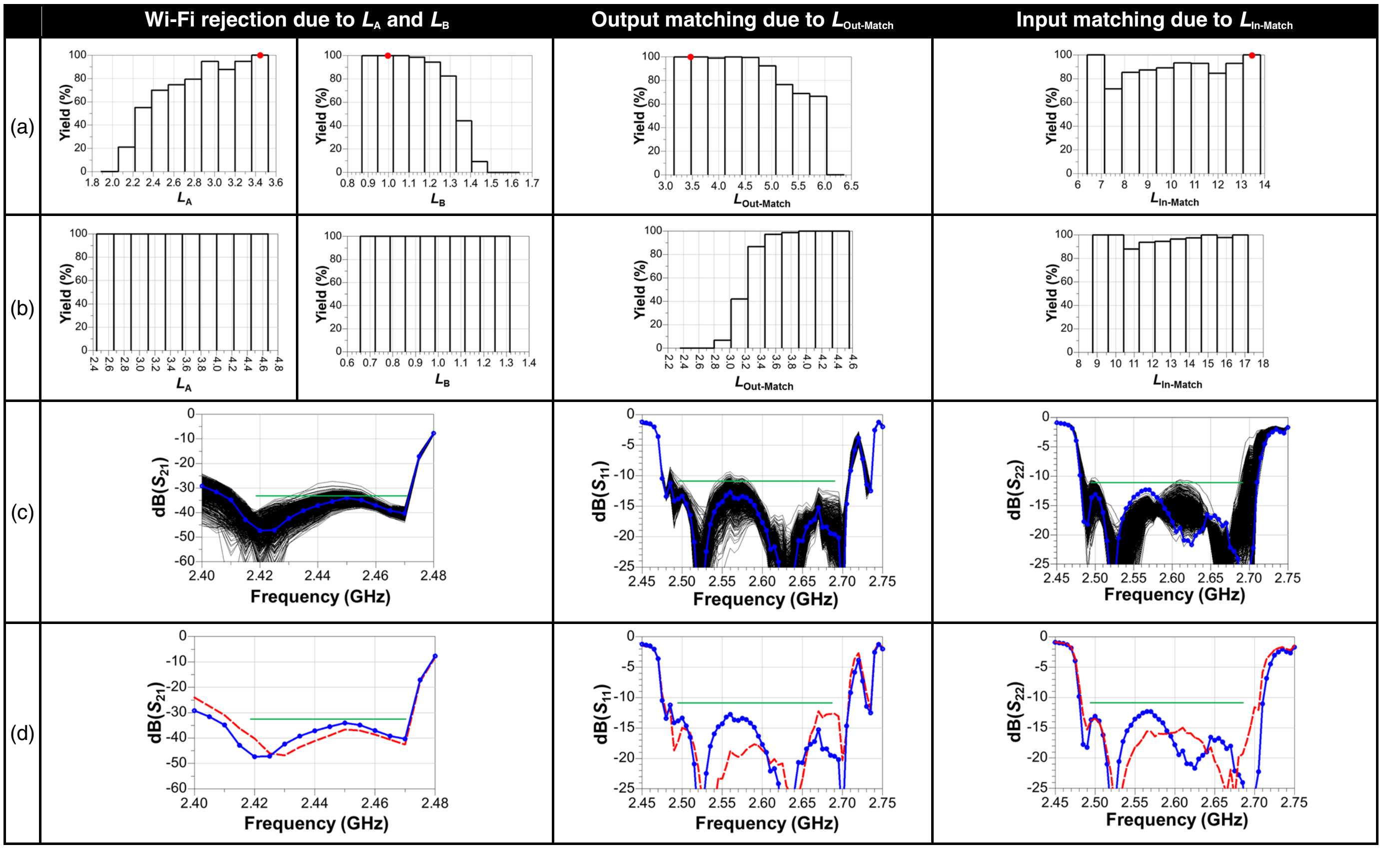

Fig. 3. (a) Yield sensitivity histograms of the nominal design of Band 41 filter upon performing MC analysis using the inductors values indicated in Table I; (b) yield sensitivity histograms upon incorporating the inductor values which result in maximum yield estimate as marked with circle symbols in the histograms shown in (a); (c) measured filter response incorporating the nominal inductor values (circle symbols) and MC simulation trials (solid curves) with design spec lines (Wi-Fi rejection covering channels 4 to 11 is -33 dB and filter's input/output matchings are -11 dB); and (d) Comparison between the measured filter response incorporating the nominal inductor values (curve with circle symbols) against the filter response obtained after optimizing the yield (dashed curve). Results obtained after MC yield optimization show the improved margin from the design spec lines.

The sample statistics (*i.e.*, mean and variance) obtained from MC experiments can vary from one experiment to another. Therefore, the sample mean can vary about the actual population mean within an error. In this context, a population is the whole group of interest that statistically represents the manufacturing induced process variation. According to [7], the margin of error (E) of a sample proportion (P) under a given confidence level (CL) or confidence interval ($Z_{a/2}$) can be calculated as

$$E \geq Z_{a/2} \frac{\sqrt{P(1-P)}}{\sqrt{N}}, 0 \leq P \leq 1 \quad (1)$$

where E is the maximum error of the estimate, N is the sample size, and $Z_{a/2}$ denotes to how many standard deviations a sample is from the mean and can be calculated from the cumulative distribution tables of a normally distributed random variable as in [7]. CL is a probability measure that determines how the estimated parameters that are obtained from the samples would represent the true population parameters within the $Z_{a/2}$ interval. Thus, CL is governed by the $Z_{a/2}$ interval.

By rearranging (1), the minimum required sample size can be rewritten as

$$N \geq \left(\frac{Z_{a/2}}{E}\right)^2 \left[P(1-P)\right] \quad (2)$$

Scrutiny of the normal distribution tables in [7] shows that the CL grows as the E grows which implies an increase in the standard deviation and thereby a wider intervals of the distribution. To illustrate, a 1σ above or below the mean in a normal distribution corresponds to a 68% confidence that the samples mean represent the entire population mean, while a 2σ above or below the mean gives a 95% confidence and this concept applies regardless of the distribution. Therefore, a high precision estimate results in less confident decision, while the more error allowance leads to more confident decision. In Section IV, a case study will demonstrate that different margins of error under a given CL will results in different number of samples required to cover the design input space. According to (2), an increase in the margin of error at a given CL translates into a reduced number of samples.

TABLE I

MONTE CARLO YIELD ANALYSIS RESULTS FOR DIFFERENT CASE STUDIES USING BAND 41 SAW FILTER

	Margin of error (%)	$Z_{a/2}$	Sample proportion (%)	Confidence level (%)	Sample size	Inductor values (nH)				Initial yield (%)	Optimized yield (%)
						L_A	L_B	$L_{\text{Out-Match}}$	$L_{\text{In-Match}}$		
Nominal	-	-	-	-	-	2.7	1.25	4.6	10.3	-	-
Case 1	±2	1.96	90	95	865	3.45	1.0	3.5	13.5	69	82
Case 2	±2	2.576	90	99	1493	3.6	1.0	3.7	13.4	71.2	80.5
Case 3	±4	2.576	90	99	374	3.5	1.0	3.6	13.3	69.8	81.8

IV. CASE STUDY

A Band 41 standalone SAW filter designed and measured in a 50 ohm system is utilized as an illustrative example to demonstrate the advantages of the MC yield optimization approach presented in Section III. For brevity, a portion of the filter topology is selected where four inductors are investigated under this study as illustrated in Fig. 2. In addition, we choose to eliminate uncertainties due to the SAW filter fabrication process and to focus solely on the variability of the added components (*i.e.*, inductors). This is performed by first measuring the filter on a test fixture and then de-embedding the measured scattering parameters to move the phase reference planes to the filter die planes. Next, the measured data of the four-port filter defined by the dashed box in Fig. 2 is utilized to mathematically incorporate the lumped inductors denoted by $L_{\text{Out-Match}}$ and $L_{\text{In-Match}}$ for matching, and L_A and L_B for placing narrow band-notches at the Wi-Fi channels 4 to 11.

With the aid of Keysight ADS [8], MC simulations combined with PRS were performed to three cases of the nominal design, each with different combination of CL and E as listed in Table I. E, P, and $Z_{a/2}$ are then used to calculate the required sample size for each of the three cases using (2). A Gaussian distribution and a tolerance range of ±10% for the inductor variables were assumed. Fig. 3(a) shows the resulting yield histograms for each of the design variables after applying the statistical parameters in Case 1 of Table I to the nominal inductor values listed in Table I. Using the inductor values resulted in highest yield as marked with circle symbols in Fig. 3(a) and tabulated under Case 1, another cycle of MC simulations was performed and the updated yield histograms were displayed in Fig. 3(b). Fig. 3(c) illustrates the filter response resulted by MC trials and compared to the nominal response. Comparison between the electrical performances before and after the yield optimization is demonstrated in Fig. 3(d). Similar procedure was also followed for Case 2 and Case 3 and their yield results were summarized in Table I. Yield result of Case 3 shows that even with a reduced sample size one can still achieve an accurate yield estimate very close to that in Case 2. Although the initial performance meets the design specs, results obtained after MC analysis and yield optimization show improved margin from the design spec lines.

V. CONCLUSION

In this paper, MC yield analysis and optimization has been incorporated at the design phase of an AW ladder-type filter as a design centering method. A standalone Band 41 SAW filter has been employed to demonstrate the yield and sensitivity improvements by virtue of MC analysis. While deterministic numerical techniques are inefficient in handling the broad and multidimensional variability of circuit elements, alternatively stochastic methods provide good coverage of a design input space allowing accurate estimation of the statistical variations.

The presented procedure offers a simple means for reducing yield loss caused by the filter's external components. Such design centering method is necessary to sustain certain OOB rejection levels and in general to insure that a given design parameter will meet the specifications within the assumed tolerances. As can be observed from the case studies in Table I, the improvement between the initial yield and the yield after optimization is approximately 10%. This improvement is very appreciable in the case of a mass-produced product.

A similar approach can be followed for centering the critical design components of an AW multiplexer as well as for optimizing a large RF module rather than performing several tedious laboratory experiments for performance tuning.

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