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A Generic Hybrid Modeling Approach for the Complete Response of Acoustic Resonator

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***Abstract*—The growing prevalence of RF acoustic filters has emphasized the need for a model for accurate resonator frequency response including spurious modes. Traditional modeling methods have their limitation and cannot fully accommodate the fast-paced design work. This paper proposes a generic hybrid modeling approach for complete response of acoustic resonators. A systematic technique is presented by splitting an acoustic resonator model into two parts: 1) the main mode is simulated by a one-dimensional non-linear circuit model and 2) spurious modes are simulated from a data-based s-parameter model. Moreover, resonator non-linearity caused by spurious modes is introduced by adding a non-linear voltage source. This hybrid model is able to predict both small signal and large signal behaviors of resonators. This modeling approach is consolidated at resonator level and is proved to be useful in the filter design.**

Keywords—Acoustic filter, SAW, BAW, Spurious Mode, Mason Model, mBVD model, non-linearity, harmonics.

I. INTRODUCTION

Acoustic filter technology, including Surface Acoustic Wave (SAW) and Bulk Acoustic Wave (BAW), has become attractive for RF front-end modules in mobile phones because of its high performance and small size. To meet challenging design specifications, resonators are expected to have high Q value, optimum piezoelectric coupling coefficient and sufficient spurious mode suppression. Due to the complexity of electro-acoustic phenomena, it remains challenging for researchers to completely suppress all spurious modes without sacrificing Q or piezoelectric coupling coefficient. Thus, filter designers have to deal with the performance impact from these modes so it is important to develop a good model for capturing the complete response of a resonator.

In recent years, companies and research institutes around the world have demonstrated different improved modelling techniques to accurately predict both small-signal and large-signal frequency domain response of acoustic resonators and filters including spurious modes. These approaches include: a) 2-D/3-D FEM-based model, which suffers from long computation time and high demanding of computing power [1]-[3]; b) Circuit model, such as multi-branch mBVD model, which cannot correlate spurious mode to resonator size or structure change and will require a lot of engineering resources to back fit the model[4]; c) Behavioral models, such as S-parameter and X-parameter models, which require huge efforts in device fabrication and measurement to establish the model database. Overall, each method has its own advantages and limitations so they cannot fully accommodate fast-paced device development and filter design work.

In this paper, a new hybrid simulation approach is proposed that allows all additional modes to be stitched together with main mode. A systematic technique is presented to split the model into two parts: 1) the main mode is simulated by 1-D model such as mBVD or Mason model and 2) spurious modes are simulated from a data-based model. Due to the small quantities of samples, the data-based model relies on the interpolation. We will describe the interpolation methodology next. Alongside the linear model, we expand the model into the non-linear region with additional harmonics features. In the end, the hybrid model enables a complete response of the resonator and thus has the ability to predict the filter behavior built in the front-end module. The accuracy of the model is validated by comparing to the measurement, and the modeling approach is proved to be useful in the filter design.

II. MODELING METHODOLOGY

A. De-embedding the main mode from complete response

The analysis starts from the Y-parameter of complete response of the resonator at each frequency of interest, which is obtained from either measurement or FEM simulation. The 1-D model such as mBVD and Mason can be extracted from Y-

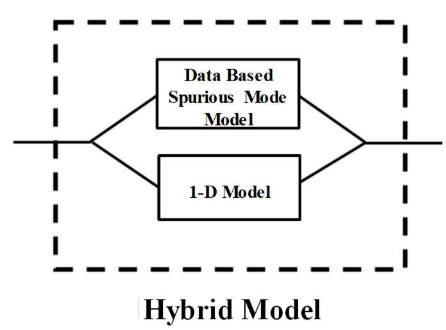


Fig.1 Model structure

parameters. For example, mBVD model with additional resistors can be extracted from resonant frequency, anti-resonant frequency, off-resonant capacitance and Q factor. The Mason model will be a little more complicated since a couple devices with different stack are required, but still feasible, and the procedures have been demonstrated in many previous publications [5]. Due to the limitation of 1-D model, either mBVD or Mason only captures the main mode response of the resonator, which will be translated into the equivalent admittance matrix.

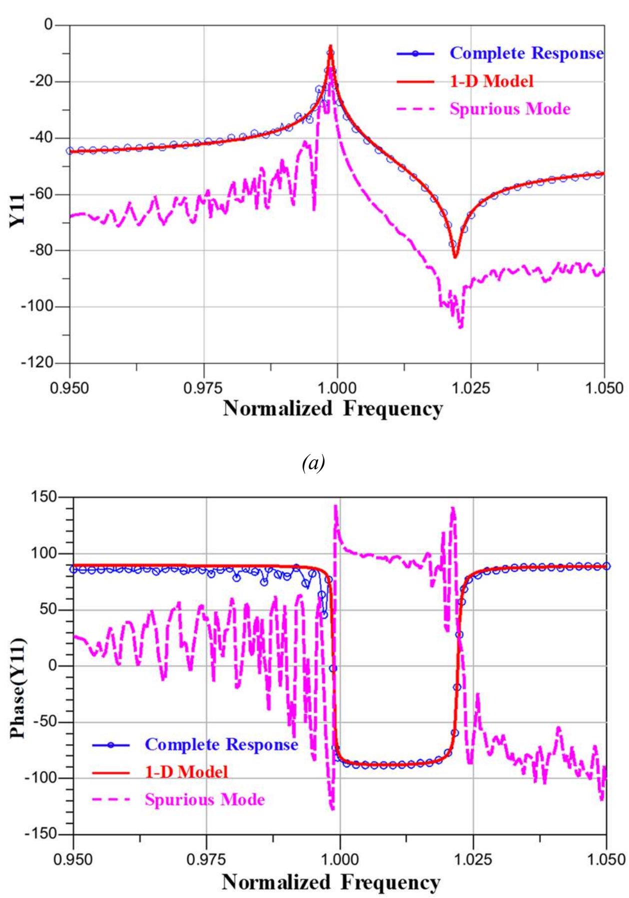
Based on the schematic proposed in Fig.1, the main mode model will connect in parallel with the spurious mode model. The spurious mode admittance matrix can be obtained by subtracting the main mode directly from the complete response as below:

$$Y_{spurious} = Y_{complete} - Y_{main} \quad (1)$$

In Fig.2, the complete response of the resonator, the main mode response from the 1-D model and spurious modes by the method above are presented. Typically, this procedure needs to be repeated on a group of devices with varying design parameters in order to get the profile of the spurious mode with respect to that parameter.

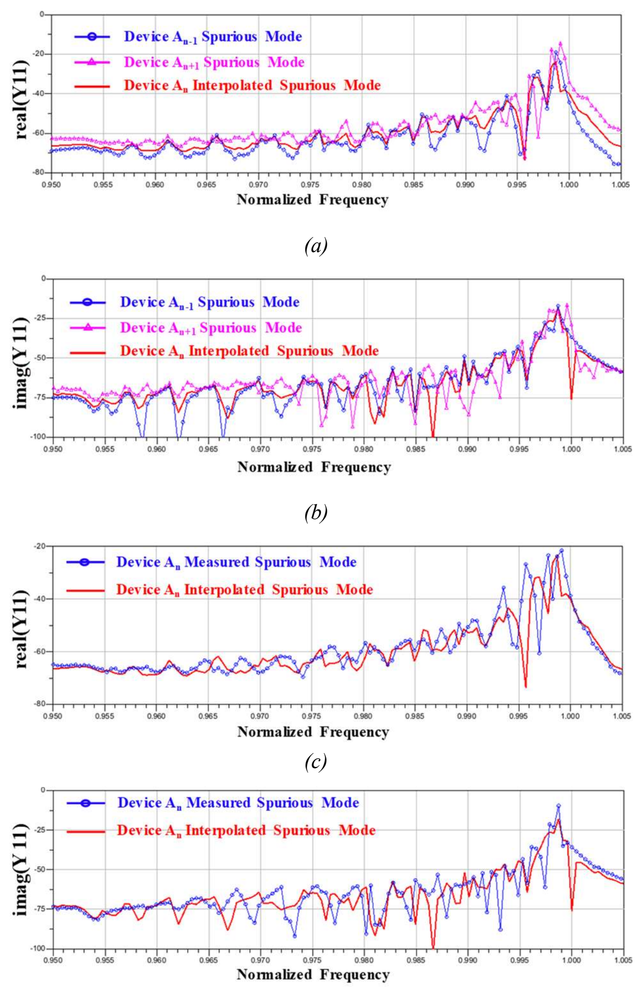
B. Interpolation Methodology of Spurious Mode

Once the admittance matrix of spurious mode is achieved, a proper interpolation method is desired in the next step. Interpolation method could be polar, rectangular, polynomial or any customized function. The data-based model is no longer limited to Y-matrix and can also be Z-matrix, S-matrix, or others. It will not make much difference if the data point density is high enough. But in our case, in order to minimize the fabrication resources and data collection time, only a couple of devices and data points are available. A proper interpolation method will minimize the errors and improve the model accuracy. Generally, a dramatic change in the variable value will increase the error in the interpolation. For example, in Fig.2(b), the phase of the spurious mode will flip at Fs and Fp, which brings potential difficulties in interpolation and is not preferred.



(b)

Fig.2 (a) Magnitude of main mode from 1-D model, spurious mode vs. complete response (b) Phase of main mode from 1-D model, spurious mode vs complete response.



(d)

Fig.3 Spurious mode interpolation from real part (a) and imaginary part (b) of Y-parameter. Real (a) and imaginary (b) part of spurious mode from interpolation vs measurement after de-embed the main mode.

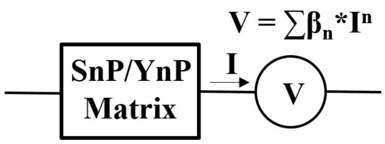


Fig.4 Non-linear model for spurious mode

In the example used in this paper, the main variable is device area, so admittance-matrix is preferred and real and imaginary part of Y-parameters are interpolated. Considering the physical mechanism of different spurious modes, we choose use high order polynomial interpolation as below:

$$Y_n = \frac{Y_{n+1} - Y_{n-1}}{f(A_{n+1}) - f(A_{n-1})}\left(f(A_n) - f(A_{n-1})\right) + Y_{n-1} \qquad (2)$$

$$f(A) = \sum k_n A^n \qquad n = 0,1,2,3\ldots \qquad (3)$$

Where A represents area of resonators.

In Fig.3, the spurious mode prediction by using high order polynomial interpolation is presented. Due to the loose density of samples, the peak of the interpolation does not exactly match the measurement. However, the overall trend and amplitude of the fluctuation from the model correlates to the measurement pretty well, which is sufficient for the design work.

If there is more than one variable to interpolate, the procedure above can be iterative, except only changing variable "area" with another variable and updating polynomial function if needed. Theoretically, the variable number is unlimited. In our practical case, 3-5 variables corresponding to the physical structure of the device are used. Therefore, we can optimize the performance with relatively reasonable simulation time.

C. Spurious Mode Non-linearity Simulation

Non-linear requirement on acoustic filters are becoming more stringent every year. As a result, harmonics introduced by the spurious mode are unneglectable. Nonlinear behaviors of acoustic devices have been studied by several authors [6]-[12] and several models are developed based on either unique physical mechanisms or a back fitting process.

Based on the methods in previous section, we obtain the admittance matrix for spurious modes. This can be upgraded to predict high order harmonics from spurious modes. We propose a non-linear voltage source in series with the linear model, which have only 2[nd] and higher order terms as below.

$$V = \sum \beta_n I^n \qquad n = 2,3,4\ldots \qquad (4)$$

A measurement-based fitting process is used to extract those non-linear coefficients β. The detailed procedure is as follows:

1) Extract a linear 1-D model (mBVD or Mason Model) for the main mode from the complete response of the resonator.

2) Establish a non-linear 1-D model by using modeling methodology from previous authors.

3) De-embed the 1-D model to get linear model for the spurious mode.

4) Add a non-linear voltage source to the spurious mode model as in Fig.4.

5) Simulate the whole hybrid model and adjust the non-linear coefficients β to calculate the mean square error between simulation the harmonics amplitude in the spurious frequencies as described in the equations:

$$Err = \sum\left(dB(Har._{meas}) - dB(Har._{model})\right)^2 \qquad (5)$$

When the error is lower than the one required, it finally returns the optimum values of βs for nonlinear coefficients.

Similar to the linear model, the non-linear model will also use interpolation method on non-linear coefficients in order to predict device harmonics regarding the change of design parameters.

III. Model Validation and Application

A. Single Resonator Model Validation

Three resonators with areas ratio 1x:3.3x:8.3x were sampled on the same wafer and measured both small and large signal responses. Three devices are defined as references whose areas are large, small and medium in the process. The target device is randomly picked. By implementing the modeling approach above, the full response of target resonator is plotted in Fig.5 and Fig.6. In the low frequency region, the model can track well the loops due to the spurious mode. Although the peaks do not exactly match, the trend and amplitude of fluctuation have good

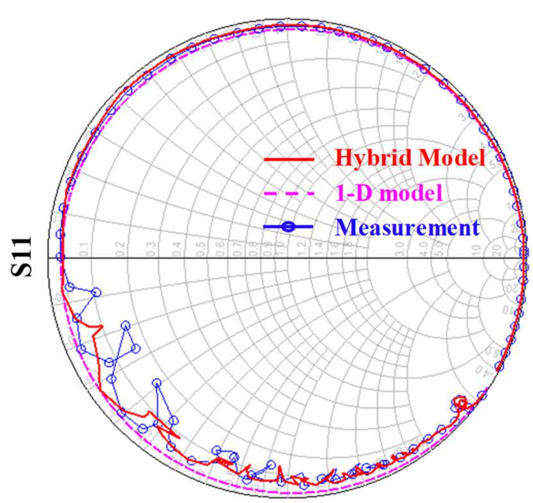


Fig.5 Small Signal Model vs. Hardware

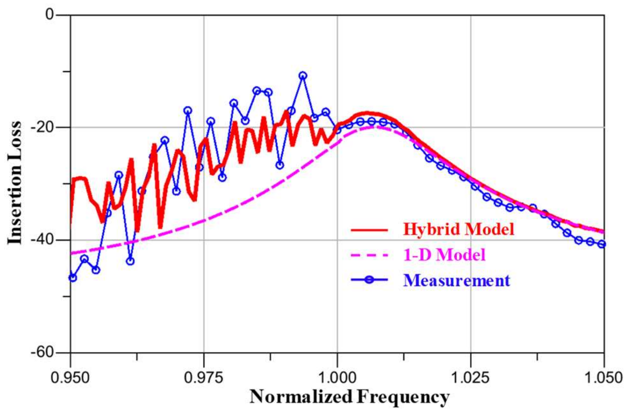


Fig.6 2nd Harmonics model vs hardware correlation

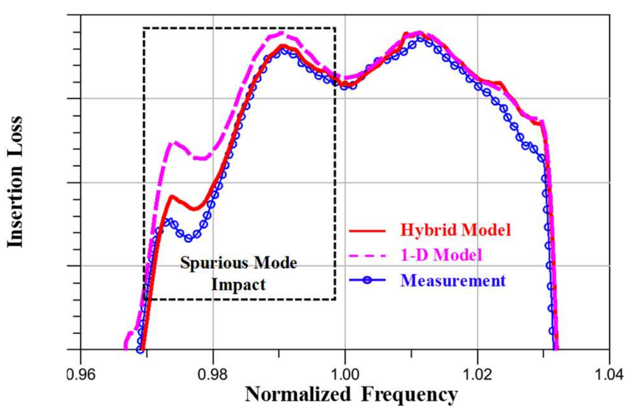


Fig.7 Pass-Band Filter Response

agreements between model and measurement. The accuracy decreases when the frequency is very close to Fs because of the rapid change in spurious modes. This can be improved by increasing sampling density regarding area. Overall, simulated responses from the hybrid model can track the trend of the spurious mode and has a good improvement compared with 1-D model for both small and large signal response.

B. Hybrid Model in Filter Design

The following simulations comprise the acoustic filter for a certain LTE band. Two simulations have been performed and compared with the measurement results. Both 1-D model and hybrid model can predict middle to high in-band frequency, but hybrid mode is significantly better in the low in-band frequency, which deals with spurious mode problem from actual resonators. There are still some discrepancies between hybrid model and measurement at the start and end of the pass band and it has been verified that those errors are introduced by parasitic in the measurement.

IV. Conclusion

The developed hybrid model has clearly shown its capability to predict the complete linear and non-linear responses of the acoustic device which can be used in the device simulation and circuit design. Based on the described methodology, a model extraction process has been discussed. Its usefulness has been demonstrated with practical samples. Moreover, this methodology presents an efficient way to extract the model to accommodate the fast-paced design work.

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