MATLAB Modeling and Simulation for SAW/BAW Devices

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1. Introduction

Nowadays, MATLAB modeling and simulation has become a standard approach for research and development of SAW/BAW devices. The computing platform *MATLAB®* (MathWorks) combines a commercial numerical computation environment with a high-level matrix-based programming language. This makes MATLAB modeling of SAW/BAW devices very attractive for scientists, researchers, and engineers working in this technical field.

Dr. Alexander Rukhlenko is an experienced SAW/BAW expert who has contributed to both the theory and practical design of SAW/BAW devices using MATLAB. His work covers many aspects of MATLAB Modeling SAW/BAW Devices, from SAW filter synthesis and analysis to multilayer FBAR simulation.

2. MATLAB SAW/BAW Modeling Experience

Dr. Alexander Rukhlenko was one of the first SAW researchers and designers to apply MATLAB to SAW filter modeling and practical design in the former USSR. Since 1993, he has systematically used MATLAB in his SAW research. As a result, he contributed significantly to MATLAB-based computer-aided design of SAW filters and devices.

He developed numerous efficient models, techniques, algorithms, and comprehensive MATLAB software tools for SAW/BAW device analysis and design. These MATLAB tools have been applied in both theoretical studies and in the practical design, modeling, and simulation of SAW/BAW devices. The resulting software spans a wide range of SAW/BAW analysis tasks and covers both component-level and system-level modeling.

Furthermore, most of his theoretical results are based on vector-matrix formulations and derivations that are particularly well suited for MATLAB-based implementation. These matrix-based solutions and closed-form expressions reflect a unified mathematical formalism for efficient numerical modeling of SAW/BAW devices. The combination of vector-matrix formalism and implementation-oriented modeling represents a distinctive feature of the research methodology developed by Dr. Rukhlenko. This systematic approach enables compact and computationally efficient MATLAB implementations across a broad class of SAW/BAW devices.

Finally, he also contributed to MATLAB modeling of BAW devices. To this end, he adapted some of his SAW algorithms and developed new methods and techniques for analysis of Thin-Film Bulk Acoustic Resonators (FBARs). In particular, he created software for modeling FBAR multilayer stacks using the Mason equivalent circuit model. A separate MATLAB program computes dispersion diagrams of multilayer FBAR structures based on the Fahmy-Adler acoustic wave propagation formalism.

His MATLAB methods and algorithms often outperform approaches published by other authors. Practical SAW/BAW device designs validated their accuracy, efficiency, and robustness.

3. Optimum and Suboptimum Design of Linear Phase SAW Filters

First, he contributed to optimization techniques for classical SAW filters with two bidirectional SAW interdigital transducers (IDTs). In particular, he was among the first SAW designers to apply the Remez exchange algorithm to practical SAW filter design.

Originally, this algorithm was developed for synthesis of Finite Impulse Response (FIR) digital filters. In contrast to FIR digital filters, a SAW filter comprises at least two acoustically coupled IDTs. Therefore, such SAW filter structures have a much more complex frequency response than FIR filters.

His synthesis method correctly accounts for and compensates the contribution of the input IDT and multistrip coupler (MSC) to the overall SAW filter response.

In a similar way, it can also compensate a broadband element factor response that distorts SAW filter passband response.

As a result, he reprogrammed the Remez exchange algorithm in Fortran and implemented it in MATLAB as the MEX file.

Furthermore, he developed a faster Remez-based technique for suboptimum SAW filter design. This approach reduced the optimization time for long multi-electrode SAW filters by orders of magnitude, with only a negligible degradation in approximation accuracy.

4. Synthesis of Non-Linear Phase SAW Filters

Later, Dr. Alexander Rukhlenko generalized linear-phase SAW filter synthesis techniques to arbitrary magnitude and phase responses. He proposed iterative methods based on linearization of the non-linear phase magnitude and phase tolerance field. At each iteration, the algorithm updates the tolerance constraints on the real and imaginary parts of the SAW filter response. The updated constraints are derived from the results of the previous iteration. The optimization procedure alternates between optimizing the real and imaginary components of the response, which correspond to linear-phase functions by definition. The procedure converges to a quasi-optimum (suboptimum) non-linear phase solution. This approach avoids classical time-consuming non-linear optimization methods (such as non-linear programming) and relies on established linear-phase SAW filter synthesis techniques and software.

In the past, he applied this technique to the design of mass-production TV SAW filters (PAL, SECAM) with prescribed magnitude and group delay responses.

5. Iterative Weighted Least Squares (IWLS) SAW Filter Synthesis

He proposed the Iterative Weighted Least Squares (IWLS) method as an alternative to the Remez exchange algorithm. IWLS is significantly simpler to implement in MATLAB and other high-level languages (C/C++, Fortran). Moreover, many standard software packages provide built-in least-squares routines, which form the core of the IWLS approach.

The method iteratively adjusts the weights of residuals in the weighted least-squares (WLS) error function until the approximation error converges to its final value. Dr. Alexander Rukhlenko proposed and implemented several reweighting schemes with reliable and fast convergence.

In its general form, the IWLS algorithm intrinsically supports non-linear phase SAW filter synthesis with arbitrary magnitude and phase or group delay specifications. However, for more precise control of magnitude and phase approximation errors, an iterative procedure that alternates between the real and imaginary components (as described in the previous section) is desirable.

Additionally, it can iteratively compensate certain second-order effects, including frequency response distortions caused by electrical circuit effects (source, load, and matching networks) as well as SAW velocity dispersion in multilayer substrates.

6. Factorizational Synthesis of SAW Filters

Dr. Alexander Rukhlenko was the first SAW designer to introduce factorizational synthesis of SAW bidirectional filters into practical SAW filter design. In many cases, this method minimizes SAW filter length and therefore reduces substrate costs.

First, the algorithm determines high-order Z-transform roots of the desired SAW filter response. Next, it distributes these roots in a systematic manner between the input and output IDTs. Finally, the procedure derives the tap weights of each IDT from its Z-transform roots.

Dr. Alexander Rukhlenko proposed several root-separation schemes that yield IDTs with different phase characteristics and apodization patterns.

The factorizational synthesis inherently results in apodized input and output IDTs located in two separate acoustic paths. Such a dual-track SAW filter topology requires a multistrip coupler (MSC) to couple the acoustic paths.

For narrowband SAW filters, withdrawal weighting or polarity weighting can approximate apodized IDTs with sufficient accuracy. This allows conversion of the dual-track SAW filter topology with an MSC into a more practical single-track (in-line) configuration.

He successfully applied this design approach to win a SAW Filter Design Competition organized and sponsored by SAWTEK Inc. (USA) in the former USSR in 1995. The CDMA SAW filter designed by Dr. Alexander Rukhlenko and manufactured at SAWTEK demonstrated the best performance among all participants.

At the time, his proprietary MATLAB root solver outperformed standard MATLAB built-in functions in terms of speed, accuracy, and numerical stability.

7. Analysis of SAW Transducers

Dr. Alexander Rukhlenko developed fast and accurate techniques for charge distribution and capacitance calculation of apodized periodic SAW transducers with arbitrary polarity sequences.

He also solved a mixed electrostatic problem in which IDT electrodes may be specified either by voltages or by charges. He applied this theoretical approach to the analysis of SAW transducers with single or interconnected floating electrodes.

Another practical application of this approach was the electrostatic analysis of non-periodic SAW transducers. He proposed discretizing a non-periodic IDT and approximating its structure using an equidistant discrete grid of periodic substructures with small floating fingers in the IDT gaps.

Later, he generalized this methodology to calculate the admittance of periodic unapodized and apodized SAW transducers. The closed-form IDT admittance expression includes radiation conductance, susceptance, and static capacitance.

The algorithm is both fast and accurate. As a result, admittance calculation for an apodized SAW transducer takes no more time than its frequency response calculation. Moreover, the Fast Fourier Transform (FFT) algorithm further accelerates both frequency response and admittance calculations when needed.

Consequently, there is no longer a need to resort to the commonly used, time-consuming subdivision of apodization patterns into uniform (unapodized) tracks for admittance calculation. This method requires double summation and is intrinsically very slow and less accurate.

For simplicity, Dr. Alexander Rukhlenko used the quasi-static IDT approximation in his algorithms wherever applicable. This assumption is valid for most IF SAW filters.

8. Modeling of Reflective SAW Transducers

His theoretical results in SAW transducer modeling are not limited to the quasi-static approximation, where interelectrode reflections are assumed to be negligible. For reflective periodic SAW transducers, Dr. Alexander Rukhlenko developed a proprietary semi-heuristic closed-form model and applied it in the practical design of RF SAW filters.

Basically, the model generalizes the widely used Coupled-of-Modes (COM) analysis. However, the classical COM model is valid for unapodized IDTs with regular polarity alternation only. Unlike the classical COM model, the generalized model supports arbitrary polarity sequences and apodization patterns.

To derive the generalized closed-form equations, Dr. Alexander Rukhlenko exploited the formal analogy between acoustic-wave and transmission-line equations. Two key parameters govern the model: the wave propagation constant and the harmonic coupling coefficient. The former can be obtained from the dispersion equation. The latter represents the coupling between the fundamental and first backward spatial harmonics. Within COM analysis, it has a closed-form expression in terms of the electrode reflection and transmission coefficients.

The final results are presented in the form of a mixed scattering matrix, comprising acoustoelectric and electroacoustic transfer functions, SAW transducer admittance, and the scattering parameters of the short-circuit IDT.

The classical COM equations follow from the model as a particular case corresponding to a uniform solid-finger SAW transducer with regular polarity alternation. In the case of reflectionless SAW transducers, the equations reduce to the quasi-static approximation.

9. Modeling and Simulation of Multiport/ Multitransducer SAW/BAW Devices

For the general case of complex multiport and multitransducer SAW devices, Dr. Alexander Rukhlenko developed and implemented efficient analysis methods. These methods are based on either SAW component interconnection mapping or direct component cascading. The resulting MATLAB algorithms are generic and versatile. They apply to device modeling at both the micro-level (individual SAW components) and the macro-level (complete SAW systems).

In other words, the same fast and numerically stable algorithms can be applied to different modeling scenarios, for example:

- cascading periodic elemental cells within a SAW component (e.g., IDT);
- cascading SAW components (e.g., multiple IDTs) within a multi-component SAW system.

In the former case, an elemental cell may represent a single IDT period containing a voltage-driven finger or finger pair. The algorithm then cascades all elemental cells throughout the transducer structure to obtain the overall IDT scattering matrix.

An example of the latter case is the analysis of a SAW filter with interdigitated IDTs. In this case, the algorithm cascades a chain of electrically connected IDTs to obtain the overall mixed scattering matrix of the complete SAW system.

In many practical cases, these techniques also make it possible to derive closed-form matrix equations for multi-component SAW systems. Such equations are particularly well suited for MATLAB implementation.

10. MATLAB Modeling Methods for Complex SAW/ BAW Devices

Dr. Alexander Rukhlenko developed two systematic approaches for modeling complex SAW/BAW devices:

1. Global mixed scattering matrix method
2. Recurrent cascading of mixed (hybrid) transmission matrices.

In the first approach, he composed the global mixed scattering matrix of a SAW system from the mixed scattering matrices of individual SAW components. Next, all coupled acoustic ports are eliminated by applying the interconnection matrix of the SAW system. The method is robust and numerically stable. However, it is computationally intensive, since it requires construction of a large global matrix and repeated matrix inversions at each frequency.

Alternatively, he developed algorithms based on the recurrent cascading of SAW components. For this purpose, Dr. Alexander Rukhlenko introduced mixed, or hybrid, transmission matrix of a SAW component. This matrix interrelates incident and reflected acoustic waves at the acoustic ports as well as electrical currents and voltages at the electric ports of the SAW component. For cascading, he applied the concept of auxiliary artificial acoustical and/or electrical ports. These auxiliary ports equalize the numbers of input and output ports and normalize the sets of input and output variables.

As a result, the cascading procedure reduces to the recurrent multiplication of the transmission matrices. The approach is particularly well suited for MATLAB implementation because it reduces cascading to recurrent matrix multiplication and avoids matrix inversion. However, when a large number of SAW components are involved, recurrent cascading may become more susceptible to numerical instability than the global matrix method.

Additionally, he suggested a very simple and elegant method to cascade SAW transducers in the quasi-static approximation, which requires minimal MATLAB programming effort.

Later, Dr. Alexander Rukhlenko extended these SAW modeling techniques to BAW devices. In particular, he implemented cascading algorithms for FBAR layer stack simulation based on the Mason equivalent circuit model.

11. MATLAB SAW Filter Analysis Toolbox (SAWFAT)

In addition to core MATLAB, MathWorks offers so-called MATLAB toolboxes. They contain dedicated MATLAB software packages for specialists in different scientific and technical fields (e.g., signal processing, digital filters, communications, etc.). In other words, MATLAB toolboxes extend basic MATLAB capabilities by providing additional highly specialized functionality.

Although MATLAB toolboxes cover a wide range of technical applications, there are no standard MATLAB toolboxes dedicated to SAW filter design and simulation.

Over the years, the accumulated SAW/BAW experience of Dr. Alexander Rukhlenko evolved into MATLAB design tools in the form of MATLAB toolboxes. As a result, Dr. Alexander Rukhlenko developed the MATLAB SAW Filter Analysis Toolbox (SAWFAT) for SAW filter design in the quasi-static approximation. The SAWFAT toolbox covers the full SAW filter design workflow, from frequency response specifications to SAW filter photomask generation.

Researchers and designers can use SAWFAT for practical SAW filter design in industry as well as for educational and training purposes in research institutions and universities. In the past, several industrial SAW companies and universities acquired SAWFAT for practical design, educational, and training purposes.

12. ADS MATLAB Interface and SAW/BAW Models PDK

In recent years, Dr. Alexander Rukhlenko has focused on integration of SAW/BAW MATLAB models into *Keysight® Pathwave Advanced Design System (ADS)*.

This approach combines MATLAB computational efficiency and flexibility with the convenience and usability of ADS for electronic circuit design.

As a result, researchers, designers, and engineers can create custom SAW/BAW models in MATLAB and use them directly within ADS. Such models may include SAW transducers, multistrip couplers, reflecting gratings, FBARs, and other SAW/BAW components. Designers can then use them in ADS just like conventional RF components.

More detailed information, including practical examples of SAW/BAW model integration into ADS, is available in the article:
ADS Interface for MATLAB SAW/BAW Models.

Web version: *Selected SAW Filter Designs of Dr. Alexander Rukhlenko*