Bulk Acoustic Wave Filter Synthesis and Optimization for UMTS Applications

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***Abstract*— This article presents a design methodology for bulk acoustic wave (BAW) filters. First, an overview of BAW physic principles, BAW filter synthesis and MBVD model is addressed. Next, design and optimization methodology is presented and applied to a mixed Ladder-Lattice BAW band pass filter for the UMTS TX-band at 1.95GHz.**

I. INTRODUCTION

The research effort in the IST-MOBILIS project aims the development of a BAW-SMR filtering technology suitable for application to mobile multi-standard communication terminals (DCS1800 and UMTS).

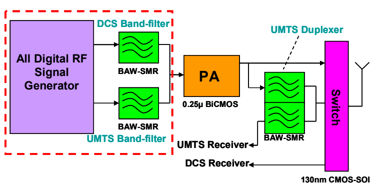

Figure 1. Architecture of MOBILIS dual-standard UMTS/DCS digital transmitter

The synthesis of microwave filters based on coupled electromagnetic resonators generally starts with the selection of a transfer function (polynomial expression) that satisfies the electrical specifications. Implementing such a methodology for BAW filters is somehow impractical since the class of realisable transfer functions is constrained by the co-existence of close resonance and anti-resonance modes of each BAW resonator. This article presents a design methodology based on a local optimisation method.

II. PIEZOELECTRIC EFFECT

Piezoelectricity is the ability of certain crystals to generate a voltage in response to applied mechanical stress (direct effect) or to mechanically deform with applied electric field (converse effect). It is a coupling between electrical and mechanical problems. It can be modelled into coupled equations (1).

$$\begin{aligned} T_{ij} &= c_{ijkl}S_{kl} - e_{kij}E_k \\ D_j &= e_{jkl}S_{kl} + \varepsilon_{jk}E_k \end{aligned} \qquad (1)$$

With :

T : mechanical stress (Pa)   E : electric field (V/m)
S : mechanical strain   D : electric displacement(C/m^2)
c : compliance tensor (Pa)   ε : permittivity tensor (F/m)
e : piezoelectric tensor (C/m^2)

Solving piezoelectric Christoffel equation demonstrate that, with a longitudinally applied electric field, three plane waves with orthogonal polarizations can propagate in the same direction with different velocities [1]. So-called quasi-longitudinal wave propagates in the electric field direction and shear waves propagate in the orthogonal plane. These waves are called Bulk Acoustic Waves (BAW). Hexagonal piezoelectric crystals, like AlN or ZnO, have a six-fold rotation symmetry. It leads to such a compliance tensor that quasi shear waves are very weakly coupled. This approximation is considered in equivalent circuit models (e.g. Mason or Butterworth-Van Dyke).

III. BAW RESONATOR STRUCTURE

Two main structures are used to build BAW resonators: Film Bulk Acoustic Resonator (FBAR) and Solidly Mounted Resonator (SMR). MOBILIS technological partner CEA-LETI is using SMR structure (Fig. 2). For Solidly Mounted Resonator, basic resonator (electrodes + piezoelectric layer) is deposited on a substrate and an alternate set of acoustic layers which present high or low acoustic impedance. This set behaves like an acoustic Bragg mirror where acoustic waves generated in piezoelectric layer reflect. It limits acoustic energy loss in the substrate. This structure is more reliable than FBAR structure, but its fabrication requires more technological steps (one step per Bragg mirror layer). A loading layer can be deposited on the top electrode surface in order to decrease resonant frequency.

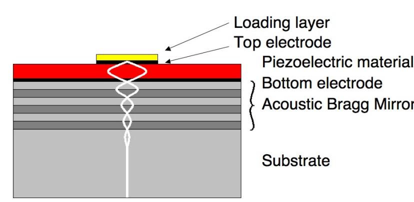

Figure 2. Solidly Mounted Resonator (SMR)

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The electrical impedance of a BAW resonator is presented in Fig. 3.

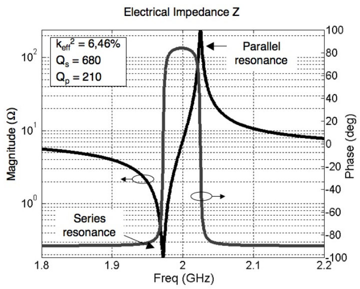

Figure 3. BAW Resonator electrical impedance

We can observe that this resonator have two main resonances: series resonance (f_s), where the electrical impedance is minimum, and parallel resonance (f_p), where the electrical impedance is maximum. For other frequencies, the resonator behaves like a capacitance.

BAW resonator can be modelled with one-dimensional equivalent circuits. Mason model based on transmission line equations needs to be able to give every layer thicknesses and every materials electric and acoustic characteristic. Lumped element MBVD Model (Modified Butterworth Van Dyke) is more convenient for BAW characterization and design.

IV. MBVD Model

MBVD model is a lumped element equivalent circuit (Fig. 4) that represents the electrical impedance of BAW resonators. It can be easily included in circuit software or analytically calculated.

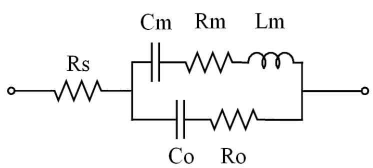

Figure 4. MBVD Model of BAW resonator

Lm and *Cm* represent the motional behaviour of piezoelectric resonators.

Co is the electrostatic capacitor given by dielectric permittivity, piezoelectric layer thickness and resonator surface.

Rm represents mechanical losses, *Rs* represents electrical losses due to electrodes and *Ro* is the electrostatic resistance.

Rm, *Rs* and *Ro* are proportional to quality factors Q_s and Q_p given at, respectively, series and parallel resonant frequencies.

$$f_s = \frac{1}{2\pi\sqrt{L_m C_m}} \quad (2)$$

$$f_p = f_s\sqrt{1+\frac{C_m}{C_0}} \quad (3)$$

$$k_{eff}^2 = \frac{\pi^2}{4}\frac{f_p - f_s}{f_p} \quad (4)$$

f_s : series resonant frequency (resonant frequency)
f_p : parallel resonant frequency (anti-resonant frequency)
k_{eff}^2 : piezoelectric coupling coefficient

V. BAW Filter Synthesis

BAW filters are usually designed using two types of resonators, namely series and shunt resonators. Since the resonators are fabricated on the same wafer, the thickness of the piezoelectric layer is fixed. Loading the top electrode is a practical process for altering the resonant frequency of shunts resonators and producing by this way a pass band response. Then, two main topologies can be used.

A. Ladder Filter

For ladder topology (Fig. 5), shunts resonators are loaded in order to match their parallel resonant frequency with series resonators series resonant frequency. In order to obtain a pass band characteristic, resonators surfaces are optimized. Ladder structure permits to obtain high selectivity, but low out of band rejection.

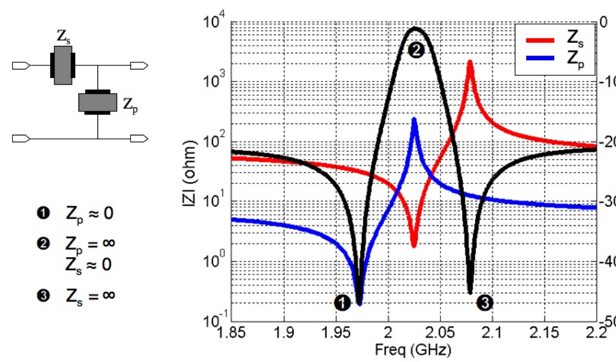

Figure 5. Ladder topology

B. Lattice Filter

For lattice topology (Fig. 6), shunts resonators are loaded in order to match their impedance level with series resonators. Lattice structure permits to obtain out of band rejection, but low selectivity.

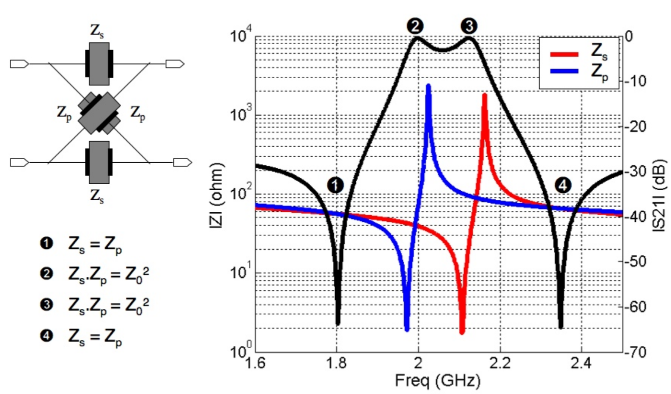

Figure 6. Lattice topology

VI. UMTS Filter Design

A. *Filter Design Methodology*

Our design methodology consists in 4 steps (Fig. 7).

1. Introduction of technological data extracted from measurements of single BAW resonators (f_s, f_p, k_{eff}^2, Q_s and Q_p)
2. Filter synthesis based on optimization of a lumped element model
3. Drawing of the layout from the synthesised filter
4. Verification analysis (co-simulation) including EM modelling of the layout

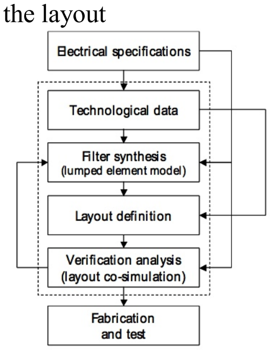

Figure 7. BAW Filter Design Methodology

Following this methodology, technological data are used for updating BAW resonator models in the filter synthesis module, regarding electrical specifications.

The filter synthesis fixes the BAW filter architecture and the characteristics of each resonator with respect to electrical specifications. The specifications consist in a pattern giving the maximum/minimum transmission values in the pass-band and stop-band regions. The main output is the surface of each resonator.

Knowing the surfaces of each resonator and the filter architecture, the layout of the filter can be drawn and a verification analysis is performed via a co-simulation including an electromagnetic modelling. Electromagnetic modelling allows characterizing both the losses due to interconnections and eventual coupling between resonators.

If the verification analysis does not meet the specifications, the layout can be modified for reducing interconnection losses or coupling between resonators. If the layout modification is not sufficient, the procedure returns to the filter synthesis step increasing margins in the transmission pattern.

The core part of the design methodology is the synthesis procedure based on the optimisation of MBVD model.

B. *Filter synthesis and optimization*

In order to synthesize and optimize a UMTS filter we have developed a homemade simulation tool. This software, using the Matlab platform, is based on MBVD model. It enables to compute complex frequency responses, such as filter, by considering BAW resonators electrical impedances for different topologies. The proposed filter synthesis procedure is described in Fig.8.

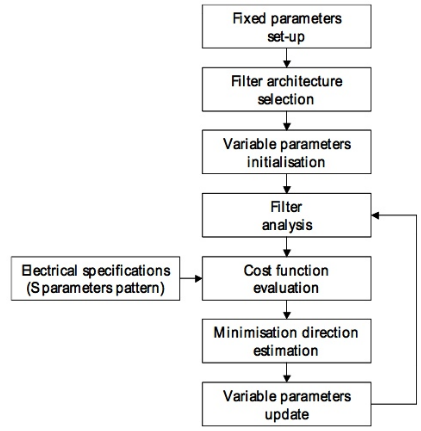

Figure 8. Filter synthesis procedure

The synthesis starts with the initialisation of resonator MBVD parameters and the selection of filter architecture.

The variable resonator parameters are optimised by minimizing a cost function which depends on S-parameters specifications. The synthesized response is optimized by performing a comparison with a given frequency pattern. It leads to a cost function calculation. Then, by minimizing this function, we can extract each MBVD element optimized value that satisfied frequency response constraints.

C. *UMTS Filter synthesis*

We performed the synthesis and the optimization of a UMTS filter where 60MHz pass band is needed for the range 1920 – 1980 MHz. Important constraints of UMTS standard [2] are a high rejection in and out of band and a high selectivity. To achieve this filter, we proposed a differential mixed Ladder-Lattice filter topology with 100Ω differential impedance (Fig. 9).

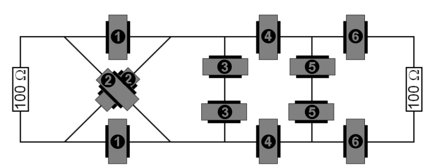

Figure 9. UMTS filter topology

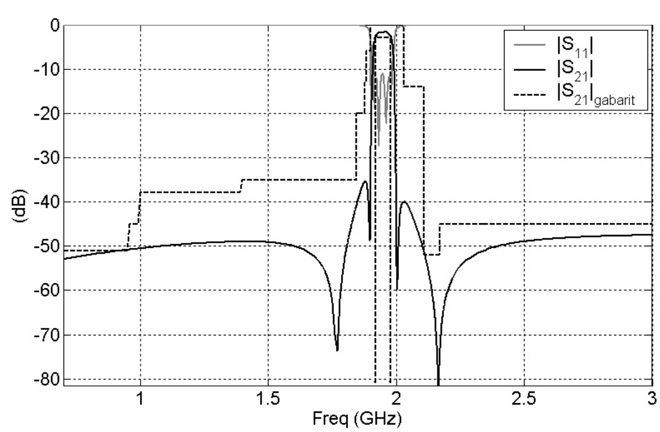

Figure 10. UMTS filter synthesis

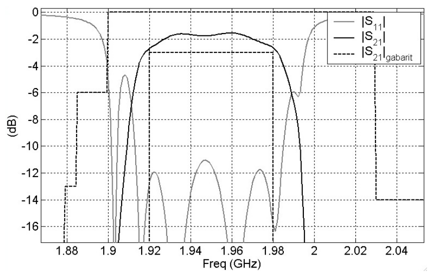

Figure 11. In Band UMTS filter synthesis

One can observe, in Fig. 10 and 11, that scattering parameters completely fulfil with given specifications.

However, filter modelling relies on MBVD models of BAW resonators, which do not take into account metallic losses or couplings due to interconnections and access ports. Since metallic lines used for connecting resonators have irregular geometries depending on the arrangement of resonators, models for such elements cannot be implemented in a synthesis tool. Nevertheless a simulation is possible a posteriori with the layout of the filter in order to estimate additional losses or to characterize eventual couplings due to metallic lines.

D. UMTS Filter electromagnetic cosimulation

The layout of the filter to be realized is drawn with an electromagnetic software, Momentum (included in Agilent ADS). Using this software, all electrostatic and electromagnetic phenomena are characterized considering the geometry and the physical characteristics of stacked layers.

The electrostatic part of MBVD resonators (*Rs*, *Ro* and *Co*) is directly taken into account in the distributed model (related particularly to the area of resonators). However, the motional part (*Rm*, *Cm* and *Lm*) is modelled through lumped elements.

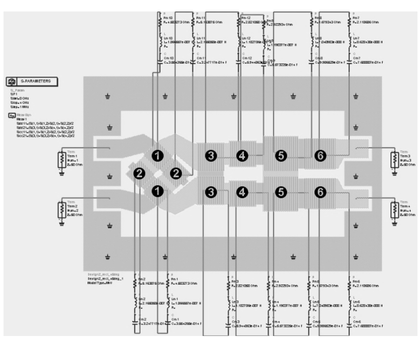

Figure 12. UMTS filter cosimulation

Fig.12 shows the cosimulation schematic in Agilent ADS/Momentum environment, including the layout and the motional parts directly derived from the previous synthesis. One can observe that shunt resonators X3 and X5 have been duplicated for symmetrizing the layout (minimization of common mode conversion).

We can notice that cosimulation filter results fulfil frequency pattern constraints (Fig. 13, black curve) in and out of band.

E. UMTS Filter measurement

This filter has been fabricated by CEA-LETI. Each resonator is deposited on a Bragg mirror (SiN/SiOC) [3] and is built with an Aluminium Nitride (AlN) piezoelectric layer, two Molybdenum (Mo) electrodes and a Silicon Oxide (SiO_2) loading layer.

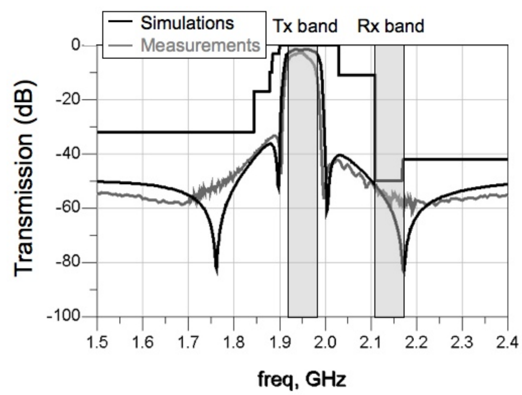

Figure 13. UMTS filter response

Differential measurement is given in Fig. 13 (grey curve). We can notice that there is a good agreement between simulated and measured responses. Insertion losses are 2.8 dB and UMTS rejection levels and selectivity are fulfilled, especially in UMTS Rx band where a 50dB rejection is required. Pass band is reduced due to slightly lower resonant frequency for series resonators during fabrication.

VII. CONCLUSIONS

In this article, we have presented a design methodology for BAW filters based on a local optimization method. Our filter synthesis software based on MBVD model is a powerful tool that permits to optimize each resonator surface with technological data extracted from measurements. Filter cosimulation step leads to simulation results very close to fabrication.

ACKNOWLEDGMENT

The authors wish to acknowledge financial support from the European Commission in the FP6 IST 2004-027003 MOBILIS project and all MOBILIS partners for contributions.

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