# Tunable acoustic RF-filters: discussion of requirements and potential physical embodiments

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***Abstract*— Multi-band / multi-system mobile phones require a complex RF-frontend architecture. Part count has increased to a point where adding switches and whole signal branches for an additional band seems no longer cost effective. Most of the active components can be adopted to work over a sufficiently wide frequency spectrum in order to cover multiple bands within one and the same circuit. This is not true for established RF filters and duplexers which are highly frequency selective but limited to operate at a fixed frequency band. It is highly desirable to create a technology which allows tuning a narrowband filter to a desired center frequency by means of an electrical control input. Concepts for tunable RF-filters – pursuing the 'holy grail' – will be discussed and an overview on the status of this matter will be presented. Existing RF-filter technologies are based on high-Q acoustic resonators realized either in Surface Acoustic Wave (SAW) or Bulk-Acoustic-Wave (BAW) technology. The paper discusses how new materials can be implemented to accomplish the goal of tunable acoustic RF filters. System requirements will be discussed and circuit concepts for the implementation will be presented.**

Keywords: Bulk acoustic wave devices, Ferroelectric devices

## I. DISCUSSION OF REQUIREMENTS FOR TUNABLE FILTERS IN FUTURE SYSTEMS

### *Tuning range:*

True interest in tunable filters is to cover at least two WCDMA bands with one filter. In the 2GHz frequency range the least demanding application would be a filter covering Band 3 (Rx = 1805 .. 1880MHz) and Band 2 (Rx = 1930 ..1990 MHz), a 11% tuning range. A combination of Band 2 with Band 1 (Rx = 2110 .. 2170 MHz) would also be desirable, requiring a 12% tuning range. Ideally such a filter would cover all three WCDMA bands 3, 2, 1 requiring a tuning range of 20%. The most challenging application would include Band 7 (Rx = 2620 .. 2690 MHz), see fig. 1.

### *Insertion loss:*

State-of-the-art filters and duplexers show an insertion loss of 3dB worst case (at the edges over full temperature range) with typical values in the range of 1.5 dB.

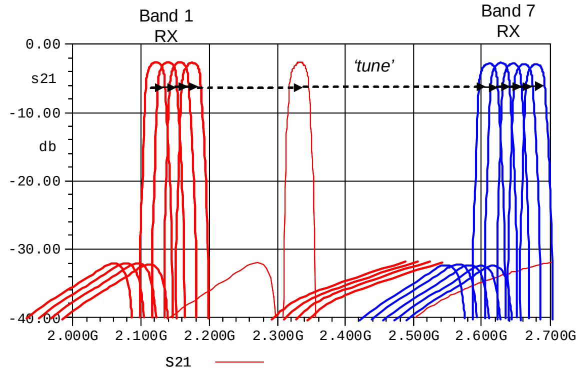

Fig 1: hypothetical tunable narrow band filter

The allowance for insertion loss for a tunable filter will not be higher than 3dB or else the sensitivity of the receiver and power consumption of the power amplifier will degrade badly. Insertion loss must maintain low up 85C ambient temperature

### *Control signal:*

The battery voltage of mobile phones is typically between 2.7 .. 3.5V. In case a higher voltage is required for tuning it would have to be provided by a boost circuit. It is feasible to generate voltages of 30V with relatively little effort, but boosting to higher voltages will require high-voltage components and will increase cost, size and power consumption of the system significantly. It is obvious that this aspect is important when judging the commercial feasibility of tunable filters. Boost circuits need have very low power consumption as they would be permanently on during operation of the phone.

### *Power handling and linearity:*

The typical maximum power in transmit operation for a WCDMA systems is 30dBm at the input of the filter. The required MTTF (mean time to failure) is 10000h at room temperature. W-CMDA also has stringent requirements with regard to linearity and related inter-modulation effects. Even in conventional acoustic filters – which were considered perfectly linear a few years back - meeting those requirements can be a challenge [1]. Inserting any additional 'inherent' nonlinear element needs to be considered carefully. The specifications to be met for type approval of a phone include continued operation in presence of interference sources – so called 'blockers'. The blocker strength and frequency is defined for each band. Worst case for intermodulation usually occurs when either of the following conditions are met:

$f_{blocker} + f_{TX} = f_{RX}$ (low frequency blocker)

$f_{blocker} - f_{TX} = f_{RX}$ (high frequency blocker)

in which $f_{TX}$ and $f_{RX}$ are the paired channel center frequencies of transmit and receive respectively and $f_{RX} - f_{TX} = const$ for each specific band (80MHz in case of band2, 190MHz for band1). The intermodulation product falling in the receive channel will degrade receiver sensitivity. Accordingly, the requirement is to prevent intermodulation products to exceed the minimum receive signal level of -100dBm or less.

*Size and cost:*

It will not be possible to charge a premium price for tunable filters in any commercial wireless application. The reference will be conventional systems using fixed filters and switches. Board space may not exceed what a conventional RF-system will require at the time of market entry.

## II. REVIEW OF THE CONCEPTS FOR TUNABLE FILTERS

*Switched Filter banks*

Technologically it is feasible to build an extensive array of individual filters at different frequencies (using SAW or BAW technology) and connect them to the input and output by multi-throw RF switches. While to the user this would appear to be a tunable filter it is practically impossible to accomplish this at reasonable size and cost. The losses of the switches and interconnections are undesirable but sometimes accepted for lack of alternatives. Solutions of this kind are limited to instrumentation and military applications.

*MEMS:*

Electrostatically actuated MEMS resonators have been proposed as a solution to nearly every filtering challenge found in RF systems [2]. However, it is unclear if MEMS can live up to this promise in the foreseeable future. Reported Q-values are very appealing, but it is obvious to RF experts that the impedance level of a filter build with such resonators would be several kOhms and thus unusable at GHz frequencies. To make things worse, the high impedance levels lead to large voltage swings - even at moderate transmit power - and will create considerable harmonic distortion and inter-modulation in the inherently non-linear electrostatical transducers. The frequency tuning effect in those MEMS devices is accomplished by the so called 'negative electrostatic spring effect'. At frequencies in the MHz range this effect is substantial, but resonators at GHz frequencies are mechanically much stiffer and the tuning effect diminishes [4].

*Tunable acoustic RF filters:*

In a BAW/FBAR device the resonance frequency is defined by layer thicknesses and acoustic material parameters of every layer present in the active area. The classical piezo-material is AlN as it possesses sufficiently high electromechanical coupling coefficient for most applications and can be deposited with excellent purity, orientation and very low acoustic propagation loss. The acoustic material parameters including coupling coefficient change very little even when applying a large DC-bias voltage across the electrodes of a BAW resonator. For a 2GHz device the frequency change is less than 20 ppm/V [3]. Clearly, this is not enough to create a tunable filter even if a DC voltage of 100V is used. Most of the reported work on tunable filters therefore focuses on materials with a stronger DC-bias effect. Candidates are Ferroelectric materials like BST which exhibit a stronger change in relevant parameters [5, 6]. The main challenge developing those materials is to considerably increase both the Q-values of resonators build with such layers and the tuning range. All acoustic parameters and the electromechanical coupling will vary as s function of DC bias.

The layers containing the highest energy density in a BAW stack tend to have the strongest influence on resonance frequency and overall behavior (fig. 2 and Table I). As a consequence it is attractive to position the tunable material between the top and bottom electrode. Unfortunately this will cause significant linearity problems as the voltage swing associated with the RF signal itself will modulate the resonance frequency of the device. Alternatives for placements of the tunable materials may have to be considered [7]. Table I shows the sensitivity of resonance frequency against acoustic velocity changes for the most sensitive layers in the stack-up of a typical BAW-SMR device at 2GHz. The obvious (and only) choice here is to use the piezolayer itself for tuning, all other (non-metal) layers – in particular the uppermost reflector layer - offer insufficient sensitivity.

TABLE I (conventional BAW SMR stack, 2GHz)

Top four most sensitive layers with regard to changes in acoustic velocity.

| *function* | *material* | *thickness [nm]* | *Sensitivity* [2] *[%$\Delta fs$ / %$\Delta vL$]* |
|---|---|---|---|
| 'tunable' Piezo-layer [1] | 'AlN' | 1300 | 0.82 |
| Bottom electrode | W | 200 | 0.026 |
| Top electrode | W | 100 | 0.014 |
| Uppermost reflector layer | SiO2 | 900 | 0.105 |

Notes: 1) Calculation based on AlN material parameters. 2) rel. changes of frequency per rel. change of longitudinal acoustic velocity

Table II shows the same result for a modified layer-stack in which the uppermost reflector layer is operating in an over-mode regime (thickness > λ/2), fig. 3. Obviously the tuning effect for the uppermost reflector layer is much enhanced compared to a traditional BAW-SMR stack.

The significant advantage of this alternative embodiment is that the tunable material is not directly subjected to the voltage swing of the RF signal, hence less likely to create strong intermodulation problems. The drawback of an over-moded configuration is that the relative filter bandwidth will shrink (as a consequence of lower $k^2_{eff}$) and that parasitic passbands can appear in the wideband response. As can be estimated from Table II it would be necessary to achieve a 23% change in acoustic velocity in order to obtain a 10% tuning range for a filter. $k^2_{eff}$ will still be in a range of 4%. Higher tuning sensitivity can be achieved using thicker tunable layers (implementing higher mode-numbers), but coupling will decline quickly while sensitivity asymptotically approaches 1.

TABLE II (over-moded BAW SMR, 2GHz)
Over-moded upper reflector layer, fig. 3

| *function* | *material* | *thickness [nm]* | *Sensitivity [%Δfs / %ΔvL]* |
|---|---|---|---|
| uppermost reflector layer 3) | 'tunable' | 5000 4) | 0.42 |

Note: 3) calculation based on SiO2 material parameters.
4) approx. 1.7 λ thickness at 2GHz

## III. CIRCUIT CONSIDERATIONS FOR TUNABLE FILTERS:

In a filter based on tunable resonators according to Table I or fig 2 it will be necessary to use DC-decoupling capacitors between all resonators, or else is will be impossible to apply bias voltage on all individual resonators needed in a ladder filter. In many reported cases for Ferroelectric materials the electromechanical coupling coefficient of the resonator changes considerably as frequency is tuned. Furthermore the static capacitance of the resonance elements changes during tuning. This creates additional challenges for filter design. At the very least the series and shunt resonators will need to be controlled separately to create a filter which matches to a certain fixed port impedance in the passband frequency range. Severe compromises in port matching are to be expected.

An embodiment in which the control-voltage-terminals are completely isolated from the RF signal is highly desirable from circuit point of view – on top of to the linearity aspects discussed earlier. This will allow tuning voltage to be supplied through biasing resistors, no DC-decoupling capacitors will be needed in the RF path between resonators. Ideally the only resonator parameter which changes during tuning is the frequency, while coupling coefficient and static capacitance remain the same. Whether such a filter can be realized strongly depends on the availability of a material which should have the following characteristics:

- change of acoustic velocity (or thickness) by at least ±10% for a control voltage not to exceed ±30V
- low acoustic propagation loss, not to exceed 0.08 dB/λ at 1 GHz.
- available as thin film of up to 10 μm (total) thickness

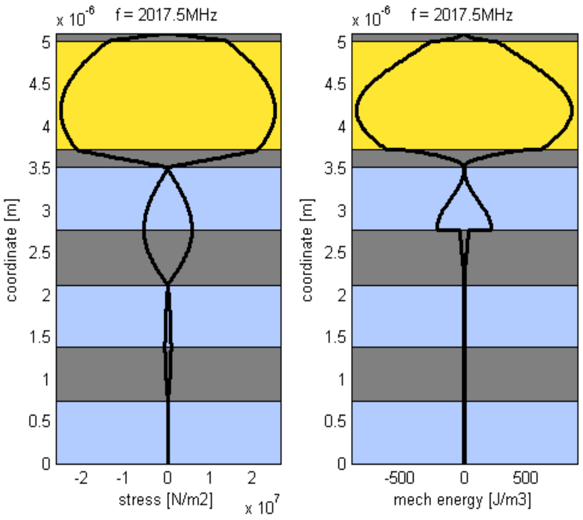

Fig.2: stress field and mechanical energy density distribution in a typical BAW-SMR layer stack. From top to bottom: Top-electrode (Tungsten), 'Piezo'-layer (or tunable material), bottom-electrode (Tungsten), acoustic reflector: 'uppermost reflector layer' SiO2, subsequent layer below are Tungsten, SiO2, Tungsten, SiO2, substrate: Si

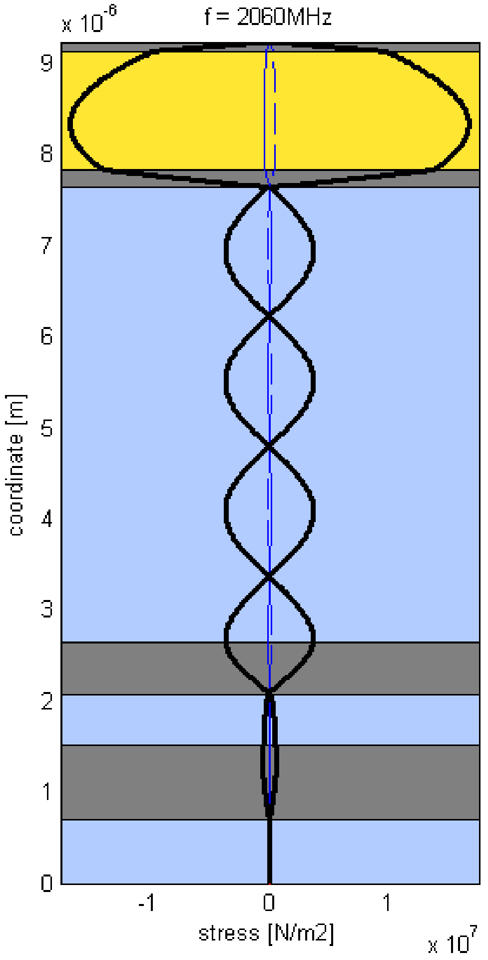

Fig.3: stress field of a resonator with over-moded reflector layer

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