Comparison of Filters with Film Bulk Acoustic-Wave Resonators (FBAR)

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Abstract – **The paper compares different architectures of FBAR filters: ladder filters, ladder filters with added extra components, lattice filters, modifications of the lattice filters. The goal of the comparison is to give an approximate estimation of the effect of different approaches in the filter design. The considerations are based on computer simulations and the main focus is on the filter frequency response: relative passband bandwidth and stopband attenuation.**

Keywords – **analog filters, RF filters, piezo-rezonators, Film Bulk Acoustic Resonators (FBAR), frequency response.**

I. Introduction

Due to their high quality factors, low losses, good temperature stability and high power handling capabilities, the bulk acoustic-wave resonators (FBAR) became widely used in the past few years in analog front-ends for realizing stable bandpass filters with good selectivity [1],[2]. Initially FBAR have been used primarily in duplexers and their success in this application caused attempts to incorporate them in other communication devices. This leads to diversification of the filter requirements: passband bandwidth extension, passband tuning, higher stopband attenuation, creating of transmission zeros at desired positions, etc.

One of the challenges of these filters is that the above requirements must be achieved with a limited set of components. In fact, FBAR filters consist of two sets of identical resonators and rarely few capacitors or inductors are added. This limitation is due to the specifics of the FBAR technology where usually the values of the parameters of both sets of resonators differ by few percent only. Usually bonding wires are used as extra inductors and sometimes these inductors are on the surface of the integrated circuit (IC) – in both cases their number is limited. The extra capacitors are connected in series to the resonator in the form of dielectric, formed on top of the piezoelectric layer. These limitations do not allow direct application of the known methods for design and synthesis of classic *LC* or quartz crystal filters. Two basic architectures for FBAR filters are known: ladder and lattice. Each of them has its advantages and disadvantages. In conclusion, the FBAR filters have limited circuit and parameter variability.

The limited filter architectures and the similarity of the FBAR parameters lead to similarity of their frequency responses. Their comparison can be done by considering of the passband bandwidth; stopband attenuation and slope steepness; existence and positioning of transmission zeros; and tunability. The goal of this paper is to do such comparison based on computer simulation of the most common filter architectures. Section II presents the used FBAR model and sections III and IV review the ladder and lattice architectures.

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II. FBAR: Parameters and Models

FBAR, as every piezo-resonator, features a series followed by a parallel resonance. It is modeled by the modified Butterworth – van Dyke model, shown in Fig. 1(a) [1],[3]. The elements C_m and L_m define the series resonance and the ratio C_0/C_m determines the distance between series and parallel resonance frequencies (typically 2-3% of the series resonance frequency). Both resonances define also the effective coupling factor k_{eff}^2 [1], which is typically few percents. The resistances are very small (around 1 Ω) which constitutes high quality factors in the range of 500 to 2000 [1]. Therefore the FBAR equivalent impedance depends primarily on its reactance, which frequency response is given in Fig. 1 (b). The basic FBAR parameters are its resonance frequencies, one of the reactive components in the mBVD model, basically C_0, and its quality factor.

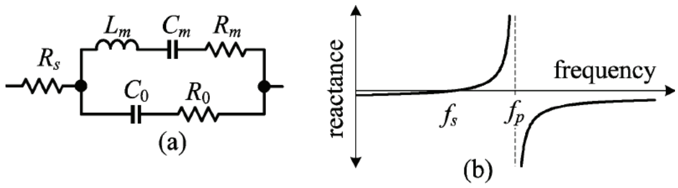

Fig. 1. (a) Modified Butterworth - Van Dyke (mBVD) model of FBAR; (b) FBAR reactance vs. frequency.

The simulations below are based on the model data given in [4]: f_s = 2.1506GHz; f_p = 2.207GHz; L_m = 69.59nH; C_m = 78.7fF; C_0 = 1.48pF; R_m = 1.027Ω; R_s = 0.8Ω; R_0 = 0.2Ω; Q≈500. These values are used for the resonators in one of the sets (set '*b*'). The parameters for the resonators from the other group (set '*a*') are determined partly artificially: their series resonance must be equal to the parallel resonance of set '*b*', C_0 and Q are the same. The corresponding parameters of set '*a*' are: f_s = 2.207GHz; f_p = 2.26496GHz; L_m = 66.08nH; C_m = 78.7fF; C_0 = 1.48pF; R_m = 1.001Ω; R_s = 0.8Ω; R_0 = 0.195Ω; Q≈500. Both sets of resonators have the same effective coupling coefficient k_{eff}^2 = 6.15%.

III. Ladder Filters

The basic ladder architecture with 5 resonators is shown in Fig. 2(a). It consists of Γ-type sections and Fig. 2(a) has 2½ sections. A single Γ-type section has very low stopband attenuation, which is the reason for cascading multiple sections to meet the filter specifications. It is clear intuitively that the higher number of sections increases also the attenuation at the passband edges, i.e. it shrinks the passband bandwidth. Therefore it is reasonable to investigate the effect of increased number of sections on the stopband attenuation and on the passband bandwidth. This is done by using PSpice and the results in Fig. 3 confirm the shrinking of the passband bandwidth when the number of sections is larger. The transfer function is calculated in the usual way for passive filters: square root from the power in the load divided by the maximum available power from the source [5]. The terminal resistances in all simulations are 48Ω.

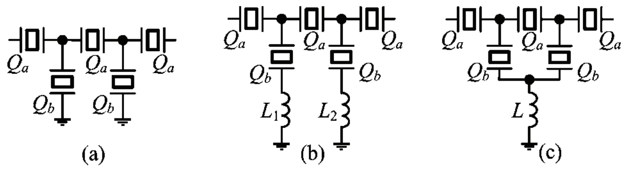

Fig. 2. (a) Basic ladder structure with 2½ Γ-type sections; (b) adding inductors in each shunt branch; (c) adding common inductor for all shunt branches.

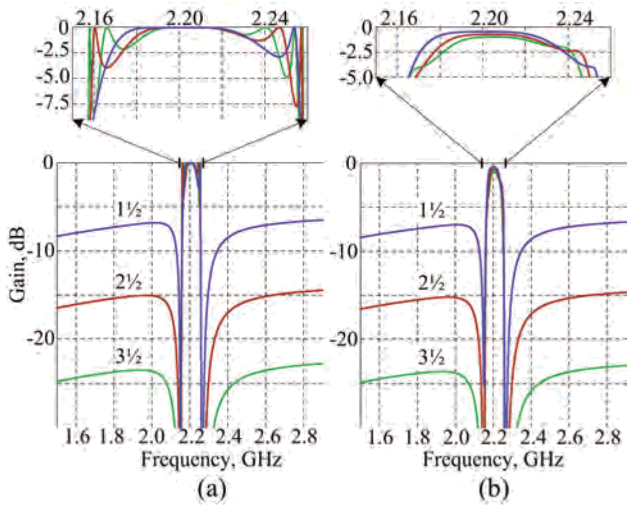

Fig. 3. Frequency response of the basic ladder filter with 1½, 2½ and 3½ sections: (a) neglected FBAR losses; (b) included FBAR losses.

The first conclusion from the simulation results is that each Γ-type section adds around 7.5–8dB attenuation in the stopband. The transmission zeros at both sides of the passband are defined by f_{sb} and f_{pa} and they do not depend on the number of sections. The simulation of the lossless circuits in Fig. 3(a) helps to clarify an interesting phenomenon in the passband: appearance of extra gain maxima beside the central passband maximum at $f_{sa} = f_{pb}$. They are due to new resonances between the resonators in the series and shunt branches. Unfortunately they are very narrow with deep gaps between them and they do not contribute for extending of the passband – their effect is just opposite. When losses are included (Fig. 3(b)) the resonance peaks are suppressed to stairs, which only extend the transition region between the stop- and passbands. This behavior is observed also in the measured filter characteristics [1].

Ladder filters can be complicated by adding of inductors in series to the shunt resonators. Connection of individual inductors to each shunt resonator (Fig. 2(b)) causes extension of the passband. The series inductor shifts the equivalent series resonance downwards, which causes the extension of the passband. A side effect is appearance of second series resonance in the upper stopband, since the order of the equivalent impedance increases [5]. The second series resonance introduces a transmission zero in the upper stopband. The shunt branch behaves as inductor above this zero, causing appearance of second passband. This is illustrated in Fig. 4(a). The higher the inductance is, the closer to the passband is the extra zero. This limits the values of the extra inductors and usually they are less than 1nH [1],[6]. Fig. 4(b) illustrates the effect of extra inductors on ladder filters with different number of sections. It is small in the stopband (the attenuation increases by approx. 1 dB). The effect on the passband is larger, when the number of the sections is bigger: for example the passband is extended by 10% for the filter with 3½ sections.

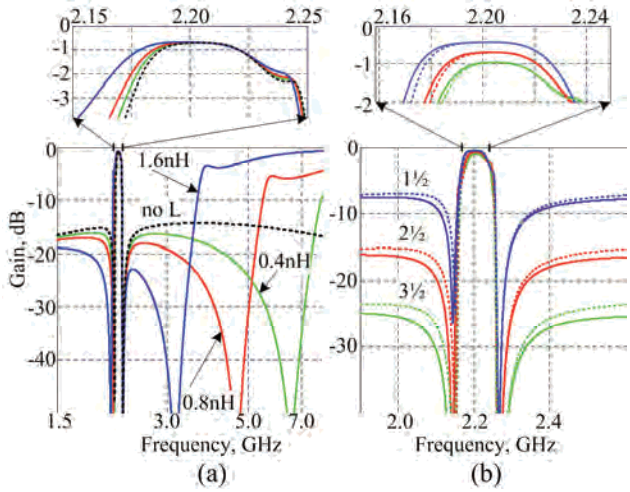

Fig. 4. Frequency responses of filters with individual series inductors (FBAR losses are included): (a) 2½ section filter with different values of the inductors; (b) filters with different number of sections and 0.4nH inductors in each shunt branch (dotted lines are for corresponding filters without inductors).

The circuit on Fig. 2(c) suggests the use of a common mode inductor that is series resonant with the set of shunt resonators [1]. It slightly increases the passband, due to the same reason as in the previous case, but its major effect is the increasing of the attenuation in the upper stopband. A second transmission zero in the stopband is introduced by this inductor, which effect is similar to the effect of the individual inductors. However a single inductor is used in this case and the simulation shows that now the reasonable value of this inductor is smaller. Fig. 5(a) compares the frequency responses of 2½ section filters without inductors, with individual 0.4nH inductors and with common 0.2nH inductor. The effect is obvious: 0.2nH common inductor gives better attenuation in the stopband of interest than two 0.4nH individual inductors. Fig. 5(b) compares 2½ and 3½ section filters with common 0.2nH inductors: evidently the effect of the inductor increases when the number of sections is bigger.

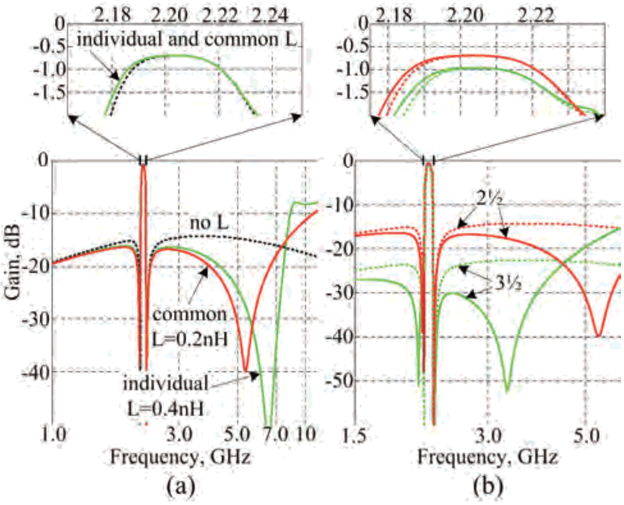

Fig. 5. (a) Comparison of 2½ section filters without inductor, with individual 0.4nH inductors and with common 0.2nH inductor. (b) Comparison of 2½ and 3½ section filters with 0.2nH common inductor (dotted lines are the frequency responses of filters without inductors).

Some numerical data are summarized in Table 1.

IV. Lattice Filters

The other common architecture for FBAR filters is the lattice structure shown in Fig. 6(a) [1],[2]. It consists of two pairs of identical resonators, for which a similar requirement as for the ladder filters is valid: the series resonance frequency of one of the pairs must be equal to the parallel resonance of the other (for example $f_{sa} = f_{pb}$). Also, the relationship $R^2 = Z_a Z_b$ is satisfied at certain frequency f_0 in the passband, where R is the value of the terminating resistors at both sides of the lattice, Z_a and Z_b are the impedances of the corresponding resonators. Theoretically there are two frequencies of maximum gain in the passband: f_0 and the frequency $f_{sa} = f_{pb}$.

Fig. 6(b) shows a modification of the lattice filter proposed in [7]. It has similar properties as the original lattice filter, when the resistances R_a and R_b are equal to the lattice terminating resistors. However R_a and R_b could differ slightly, which allows creating and tuning of transmission zeros. The first amplifier is transconductance amplifier and the second one is transresistance amplifier.

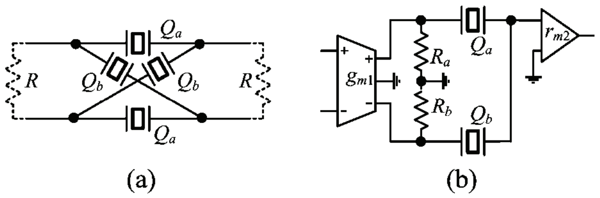

Fig. 6. (a) Lattice FBAR filter;
(b) its modifications with less number of resonators.

The simulations of both lattice filters in Fig. 6 are done for two values of the resistors R (R_a and R_b in Fig. 6(b)). The first value 48Ω ensures coinciding of the frequencies f_0 and $f_{sa} = f_{pb}$ – then the frequency response in the passband has flat behavior. The other value is 96Ω. Then f_0 is far from $f_{sa} = f_{pb}$ and close to f_{pa}. The whole passband is moved upwards and it has two ripples: one at $f_{sa} = f_{pb}$ and another at f_0. The frequency responses are shown on Fig. 7. When the losses are not taken into account the frequency responses of both circuits in Fig. 6 are identical. Their difference in Fig. 7(b), when the losses are included, is due to the input impedance of the second amplifier in Fig. 6(b), which is taken to be 5Ω. For comparison, the corresponding frequency responses of 3½ stage ladder filter taken from Fig. 3 are given in Fig. 7 also.

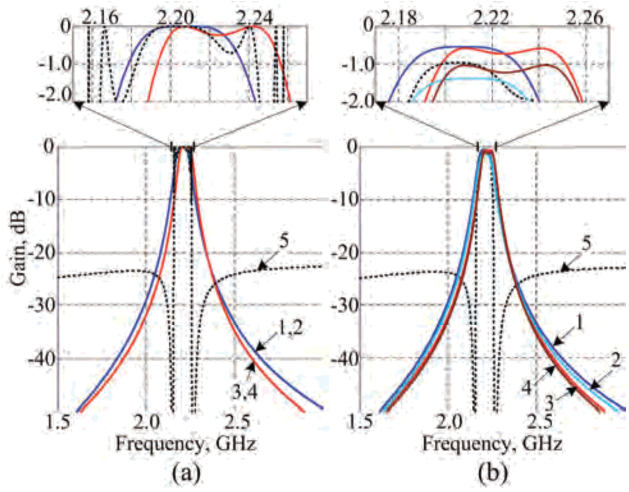

Fig. 7. Frequency responses of the lattice filters: (a) without FBAR losses; (b) with losses. Curve enumeration: 1 – the filter from Fig. 6(a) with flat passband; 2 – Fig. 6(a) with ripples in the passband; 3 – the filter from Fig. 6(b) with flat passband; 4 – Fig. 6(b) with ripples in the passband; 5 – the ladder filter from Fig. 2(a) with 3½ sections.

The comparison of the characteristics of the considered basic filter structures shows that the ladder filters have significantly narrower passband. The ladder filter ensures steeper slopes and very high attenuation close to the passband, which is due to the multiple transmission zeros in that region. This high attenuation is in narrow bands at both sides of the passband and the attenuation degrades very fast away from them. The width of the bands with high attenuation is approximately the same as the passband bandwidth. The lattice filters have opposite behavior. Their attenuation increases monotonically and not far from the zeros of the ladder filter exceeds the ladder filter attenuation.

The FBAR losses in lattice filters have the same effect as in the ladder filters. Their influence is relatively small in the stopband and the major effect is in the passband. The passband insertion loss in the lattice filters is approximately the same as in the ladders, but the shrinking of the passband bandwidth is much less. There is an increase of the insertion loss in the modified lattice filter in Fig. 6(b) due to the input impedance of the transresistance amplifier. However this could be compensated by the amplifiers.

Transmission zeros can be also created in the lattice filters. It can be done via changing of the capacitance C_0 in the mBVD model of one of the resonators (technologically this resonator should have larger area). The same effect could be achieved in Fig 6(b) by making R_a and R_b different. Examples of the corresponding frequency responses are shown in Fig. 8.

The position of the transmission zeros could vary depending on the relative difference between R_a and R_b.

Table I makes a brief comparison between both basic FBAR filter architectures, based on numerical data extracted from the frequency responses shown in the pictures above.

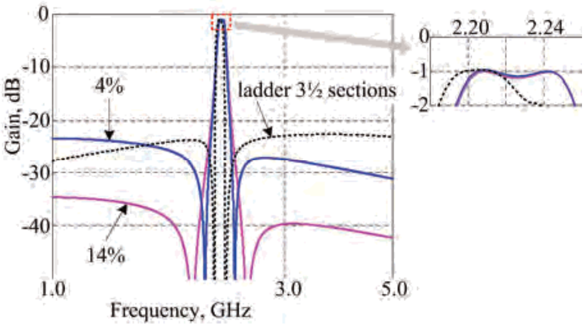

Fig. 8. Frequency responses of the filter in Fig. 6(b) when R_a and R_b are different. The percentage values give the relative difference between R_a and R_b.

TABLE I
SOME NUMERICAL DATA EXTRACTED FROM THE SIMULATED FREQUENCY RESPONSES.

	Min. attenuation in lower stopband, dB	Min. attenuation in upper stopband, dB	Min. attenuation in passband, dB	Passband width at 0.3dB, MHz
Fig. 3(a), 1½ / 2½ /3½ sections	6.8 / 15.0 / 23.5	6.1 / 14.0 / 22.3	0 / 0 / 0	45.7 / 36.7 / 32.3
Fig. 3(b), 1½ / 2½ /3½ sections	6.6 / 14.5 / 22.7	5.9 / 13.6 / 21.6	0.45 / 0.72 / 0.99	40.6 / 32.4 / 26.5
Fig. 4(b), 1½ / 2½ /3½ sections	7.1 / 15.5 / 24.0	7.1 / 15.7 / 24.5	0.42 / 0.69 / 0.96	42.8 / 34.5 / 30.4
Fig. 5(b), 2½ / 3½ sections	15.5 / 25.9	16.1 / 29.1	0.69 / 0.96	34.6 / 31.1
Fig. 7(a), flat passband	30.2*	28.4*	0	42.4
Fig. 7(a), passband with ripples	31.7*	31.1*	0	51.9
Fig. 7(b), flat passband, lattice	29.9*	28.2*	0.54	40.3
Fig. 7(b), passband with ripples, lattice	31.3*	30.6*	0.58	50.37
Fig. 7(b), flat passband, modified lattice	29.8*	28.4*	1.39	41.2
Fig. 7(b), passband with ripples, modified lattice	31.5*	30.8*	1.04	51.4

* The stopband attenuation of the lattice and modified lattice circuits is measured at frequencies, which are at ±10% from the passband center frequency.

V. CONCLUSION

The comparison of the characteristics of the two major FBAR filter architectures, done in the paper, allows to outline their pros and cons. The ladder filter features better rectangularity of the frequency response around the passband, especially when multiple Г-type sections are used. However the positions of their transmission zeros depend strongly on the used resonators and their change can be very small using the proposed techniques. Outside of narrow bands around the passband the attenuation quickly returns to moderate values. Also the passband bandwidth is typically less than that of a lattice filter. The lattice filters also have steep slopes and they may have monotonically increasing attenuation in the stopband. In addition, it is possible to create transmission zeros in the stopband, which can be positioned everywhere. The modified lattice filter in Fig. 6(b) allows also easy tuning of these zeros.

Of course, "the best filter" does not exist and every application requires its own filter. The results reported in the paper can be used for making the proper choice. These results are extracted by using a particular example. However it is not difficult to extend the conclusions for other cases. For example, different coupling coefficient will change proportionally the bandwidths and the distances between basic filter frequencies; different values of the capacitances require typically different loads; etc. Thus the reported results are not limited only to the considered examples.

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