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# DESIGN OF WIDE BAND TRANSVERSELY COUPLED RESONATOR FILTERS ON QUARTZ

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*Abstract* – Typical relative bandwidth of transversely coupled resonator filters (TCRF) on quartz wafers varies between $BW$ =0.05 to 0.1%. In this paper, we investigate the factors restricting the bandwidth and describe some specific features of designing TCRF with more expanded bandwidth $BW$ =0.15-0.3%, on quartz. The results of investigation are illustrated by experimental characteristics of four TCRF types: 315 MHz filter with $BW$ =0.28%, 248 MHz filter with $BW$ =0.18%, 402 MHz filter with $BW$ =0.125% and 360 MHz filter with $BW$ =0.064%. All filters are manufactured on quartz wafer, cut 33.3°-YX, in packages SMD 3.8x3.8x1.4 mm.

## 1. INTRODUCTION

Transversely coupled resonator filters (TCRF) are widely used in the frequency range 70 - 1000 MHz. They have high selectivity $UR$ =50-60 dB, low shape factor $SF$ =1.5-1.8, and insertion loss $IL$ =2.5-6.0 dB [1,2]. Specifically, TCRFs on quartz wafers are commonly used because they have good temperature stability and steep skirts characteristics. A typical TCRF structure includes two sections each composed of two acoustically coupled one-port resonators. A precisely tuned external coil provides electric coupling between the sections. In such TCRF with combined acousto-electric coupling the sensitivity to the inductance of the external coil increases with bandwidth. This restricts maximum bandwidth and, hence, wide-band operation. Usually the relative bandwidth of such filters at level -3 dB does not exceed $BW = \Delta f_3 / f_0$ =0.1-0.12% [1].

Several design approaches have been proposed for implementing single-section filters with pure acoustic coupling between resonators to expand the relative bandwidth. One approach uses structures of section with three [2] or four [3] acoustically coupled resonators to increase the number of useful transverse modes. Another approach combines two longitudinal modes and two transverse modes to achieve the four-pole response of the filter [4].

In this paper, we have investigated the factors restricting the maximum bandwidth in multi-resonator filters with relatively wide bandwidth: acoustic or electric coupling between resonators, matching of the utmost (the first and the last) resonators, spurious resonances in the stop band.

We exploited two models. The modified Mason model of equivalent circuits [5] was used to design a single one-port resonator or a pair of acoustically coupled resonators both at fundamental and spurious modes. The model of equivalent electrical ladder circuit of monolithic crystal filters (MCF) [6] was used to estimate the characteristics of multi-section TCRFs.

## 2. ANALYSIS OF MULTI-RESONATOR STRUCTURES

### 2.1. Structures with pure acoustic coupling

Multi-resonator TCRF can be modeled as a four-port network formed of input and output electro-acoustic transducers (EAT) and cascade-connected acoustic resonators. The elements of acoustic and electric coupling provide inter-resonator links and connect the resonators with EAT. The TCRF transfer function is determined by frequency dependent processes in all components, namely, transducers, resonators, coupling elements, and matching circuits. Given amplitude ripples and GDT in the pass band, the coupling coefficient between adjacent resonators depends on the filter transfer function (Chebyshev's, Butterworth's, Gauss's, etc.). We consider only filters with Butterworth's transfer function. This function has the minimum amplitude ripples and maximum flat GDT in the pass band [7].

Discuss firstly the restrictions upon the maximum bandwidth imposed by the properties of an infinite acoustic system with identical purely acoustically coupled resonators. In a narrow frequency band, two (three, four and so on) acoustic resonators can be treated as coupled RLC electric resonators. The electric scheme of such a system resembles that of monolithic crystal filters (MCF) (Fig.1, 2). When the resonators are identical, the normalized coupling coefficients between electric resonators are $K_{ij} = C_i / C_{ij}$, where $C_{ij}$ is equivalent capacity of coupling. The transfer function of such a system has a number of maxima at coupling frequencies $f_m$ in the pass band. For filters of order $M$ =2-6, the number of extrema equals the number $M$ of coupled resonators. The $K_{ij}$ value determines the spacing between the extrema. We consider that the spacing between the first and the last extrema (coupling frequencies $f_1$ and $f_M$) equals the bandwidth of an $M$-resonators filter, i.e. $\Delta F_M = f_M - f_1$.

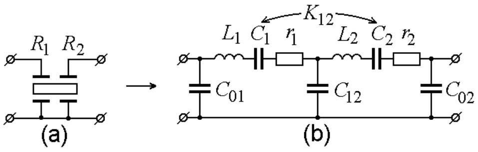


*Fig.1. Two acoustically coupled resonators (a) and their equivalent scheme (b)*

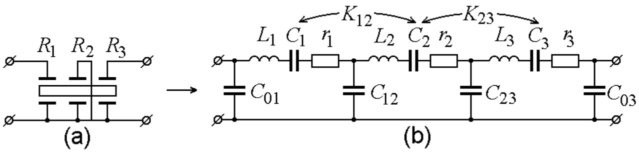


*Fig.2. Three acoustically coupled resonators (a) and their equivalent scheme (b)*

It can be shown that the bandwidth in a system of two coupled resonators ($M$ =2, Fig.1) is

$$\Delta F_2 = \Delta f_{12} = K_{12} \cdot f_0 ,$$

where $f_0$ is the center frequency of a filter, $K_{12}$ is the normalized coupling coefficient between resonators in the electric filter-prototype [7].

The bandwidth in a system of three coupled resonators ($M$ =3, Fig.2) is

$$\Delta F_3 = \Delta f_{12} + \Delta f_{23} = f_0 \sqrt{K_{12}{}^2 + K_{23}{}^2} .$$

The ratio of normalized coupling coefficients of the third-order filter-prototype ($M$ =3) with Butterworth's transfer function is $K_{12} : K_{23}$ =0.707 : 0.707 [7] so that $\Delta F_3 = 1.41 \cdot \Delta F_2$.

The bandwidth in a system of four coupled resonators ($M$ =4) is

$$\Delta F_4 = \frac{f_0}{\sqrt{2}} \left\{ \left(K_{12}{}^2 + K_{23}{}^2 + K_{34}{}^2\right) + \right.$$
$$\left. + \left[ \left(K_{12}{}^2 + K_{23}{}^2 + K_{32}{}^2\right)^2 - 4\left(K_{12}{}^2 \cdot K_{34}{}^2\right) \right]^{1/2} \right\}^{1/2}$$

In order for the transfer function to be Butterworth's one, there must be $K_{12} : K_{23} : K_{34}$ =1.0:0.64:1.0 [7] and, hence, $\Delta F_4$ =1.38 $\Delta F_2$.

With increasing number of resonators ($M$ >5-6) some of extrema merge into one extremum and the bandwidth $\Delta F_M$ hardly expands.

Let us pass from the system of coupled electric resonators to TCRF with purely acoustically coupled piezoelectric SAW resonators by replacing $K_{ij}$ with corresponding coefficient of acoustic coupling $k_{ij}$. The strength of acoustic coupling between two adjacent resonators in TCRF is governed by the distance between them in transverse direction. At 400-800 MHz this distance (bass bar + space + bass bar) is commonly $\delta$ =1.0-1.2 $\lambda_0$ when the resonator aperture is $A$ =(4-8) $\lambda_0$ [5,8]. In this case, the maximum coefficient of acoustic coupling is $k_c$ =(0.14-0.18)% for filters on *yxl* /(33-42)$^o$ cuts [5,8]. At lower frequency the inter-resonator distance can be decreased to $\delta = \lambda_0 / 4$ and then $k_c$ =0.35% for $A$ =4.6 $\lambda_0$ [9]. For estimations, we choose the maximum coupling coefficients $k_c$ =0.18% and $k_c$ =0.35% corresponding to typical $\delta$ =1.0 $\lambda_0$ and maximum $\delta$ =0.25 $\lambda_0$ feasibility of photolithography.

In this case, we obtain the following values of maximum relative bandwidth $BW_M = \Delta f_M / f_0$ of TCRF with purely acoustically coupled resonators: $BW_2$ =0.18% (0.35%) at $M$ =2; $BW_3$ =0.254% (0.494%) at $M$ =3 и $BW_4$ =0.248% (0.483%) at $M$ =4.

Thus, given Butterworth's transfer function, the maximum bandwidth is reached for the system of $M$ =3 acoustically coupled resonators. Further increase of the number of resonators hardly expands the bandwidth. The bandwidth of quartz TCRF with pure acoustic coupling is controlled by feasibility of photolithography and can be $BW_3$ =0.494% at 400-800 MHz for $M$ =3. The bandwidth can increase at lower frequencies.

### 2.2. Structures with combined acousto-electric coupling

#### 2.2.1. Filters with capacitive electric coupling

A shortcoming of TCRF with pure acoustic coupling is that with increasing number of resonators the strength of acoustic coupling grows more strongly at spurious resonant frequencies in the stop band than at the fundamental mode frequency. Accordingly, being determined by the excitation of transverse and longitudinal parasitic modes, the level of spurious resonances also grows with the number of resonators. The presence of spurious resonances is the main reason restricting the filter bandwidth. To suppress spurious resonances, the sections of two ($M$ =2) or three ($M$ =3) acoustically coupled resonators are commonly used in designing TCRF. The acoustic coupling between middle resonators is replaced with electric coupling, optimal only for the fundamental mode. The equivalent scheme of TCRF with such an acousto-electric coupling between two pairs of resonators is shown in Fig. 3. The values of coefficients of acoustic coupling $k_{12}$ and $k_{34}$ correspond to the analogous values in the above-considered system of four purely acoustically coupled resonators. The factor confining the bandwidth of the filter with combined coupling is the coefficient of electric (capacitive) coupling between middle resonators 2 and 3 $k_{23} = C_i / 2C_0 \approx [(f_a - f_s)/f_a]$, where $f_s$ and $f_a$ are resonant and anti-resonant frequencies, respectively, $2C_0 = (C_{02} + C_{03})$, $C_{02}$ and $C_{03}$ are static capacities of resonators. One-port SAW resonators with aperture $A$ =(4-8) $\lambda_0$ on *yxl* /(33-42)$^o$ quartz commonly possess $C_i / 2C_{0i} \approx$ 0.03-0.034% [5, 10] so that $k_{23}$ =(0.03-0.034)%.

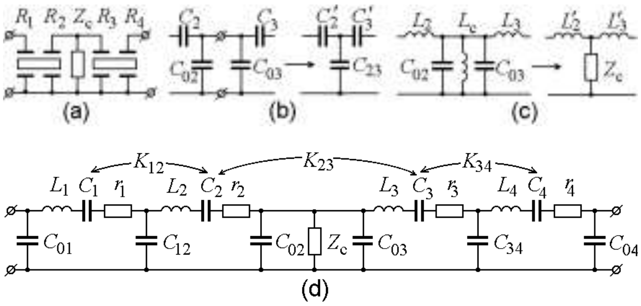


*Fig.3. Four resonators with combined acousto-electric coupling (a), transformation of coupling elements (b, c) and equivalent scheme of coupled resonators (d)*

In the four-order ($M$ =4) filter-prototype loaded on the characteristic impedance, the normalized coupling coefficients equal $K_{12} : K_{23} : K_{34}$ =0.84:0.54:0.84, respectively [7] or $k_{12} : k_{23} : k_{34}$ =0.053%:0.034%:0.053%. With this in mind, we obtain the maximum bandwidth $BW_4$ =1.85 $k_{23}$ =0.0556%. The capacity of package $C_A$ connected in parallel with $C_{02}$ and $C_{03}$ further limits the real filter bandwidth.

2.2.2. Filters with modified acoustic coupling

Several methods can be used to expand the bandwidth limited by capacitive coupling: modification of normalized coefficients in the filter-prototype, complete compensation of coupling capacity $C_{23}$ by external inductance coil and substitution of inductive coupling for capacitive one.

Following the first method, in the four-order filter-prototype having the coupling coefficient $K_{23}$ =0.54 fixed, one can increase coupling between utmost resonators to $K_{12} = K_{34}$ =1.5-1.9 keeping the required magnitude of amplitude ripples and GDT. Such an increase causes the deviation of the transfer function from Butterworth's one, since the shape factor $SH = BW40 / BW3$ becomes impaired and insertion loss grow because of matching problems to be discussed bellow. Calculations yield that insertion loss change from $IL$ =2.7 dB to $IL$ =6.5 dB for bandwidths $BW_4$ =0.04-0.125%, respectively. As to the shape factor, it impairs, increasing from $SH$ =3.2 for ideal Butterworth's function to $SH$ =4.0 for quasi Butterworth's function. Thus, we can consider that a filter involving one pair of two-resonator sections with combined acousto-electric coupling exhibits the maximum bandwidth $BW_{4\max}$ =0.125% without additional external elements, insertion loss being reasonable ($IL$ =6.5 dB). By analogy one can show that a filter involving a pair of three-resonator sections with combined coupling has $BW_{6\max} \approx$0.18% at $IL$ =6.0 dB.

2.2.3. Filters with compensated capacitive coupling

The coupling capacity $C_c = 2C_{0i}$ is compensated at the center filter frequency $\omega_0$ by connecting an external inductive coil in parallel (Fig.3). At the resonance frequency $f_0$, i.e. at $\omega_0 L_c = 1/\omega_0 C_c$, the coupling impedance becomes purely resistive $Z_c = Q_c / \omega_0 \cdot 2C_{0i}$. In this case, the coupling coefficient between resonators 2 and 3 is $k_{23} = Z_c / Z_{ci} = Q_c \cdot C_i / 2C_{0i}$, or $k_{23}$ =1.36% at $Q_c$ =40.

Hence, if an external coil is used, then the factor, which sets a limit on the filter bandwidth, is the maximum acoustic coupling coefficients between utmost resonators $k_{12} = k_{34} = k_c =$ 0.35% rather than electric coupling between middle resonators. Keeping the ratio $K_{12} : K_{23} : K_{34}$ =0.84:0.54:0.84 [7] or $k_{12} : k_{23} : k_{32}$ =0.35%: 0.225%:0.35% for Butterworth's transfer function we obtain the maximum bandwidth of a two-section filter with two resonators per section and compensating external coil $L_c$ between sections: $BW_{4\max}$ =1.85·0.225=0.42%.

The maximum bandwidth of a filter involving one pair of three-resonator sections is $BW_{6\max}$ =0.43%.

2.3. Matching of utmost resonators as a limiting factor for filter bandwidth

The output impedance of TCRF on quartz is commonly $|Z_{out}|$=1-3 kΩ. Therefore, in order to match the standard load 50 Ohm, one has to transform the impedance of 50 Ohm into the terminating impedance $R_T$. This impedance must be close to $|Z_{out}|$. Let the load of the output EAT (the last resonator) be the parallel-connected matching coil $L_M$ and the terminating impedance $R_T$ (Fig.4).

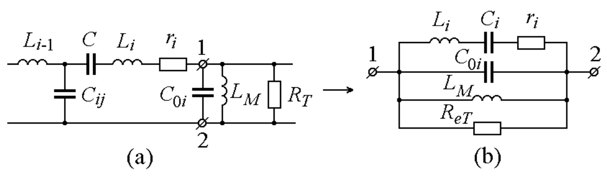


*Fig.4. The last loaded resonator (a) and its equivalent scheme (b)*

Consider two circuits thus formed: series-connected circuit (acoustic) $L_i - C_i - r_i$ with quality factor $Q_A = \omega_0 L_i / r_i$ and parallel-connected circuit (electric) $L_M \| C_0 \| R_T$ with quality factor $Q_E = \omega_0 L_c / r_c$. Let the two circuits be tuned to the same frequency. It can be shown that the series-connected circuit is then loaded on the resistance $R_{TE} = R_T \| R_{0E}$, where $R_{0E} = Q_E / \omega_0 C_{0i}$ and the quality factor of the equivalent acoustic circuit goes down to the value $Q_{AE} = Q_A \cdot r_i / (r_i + R_{TE})$. Therefore the bandwidth of the equivalent acoustic circuit formed by the output resonator-transducer, which is normally fixed equal to the filter bandwidth, increases up to the value

$$BW = f_0 / Q_A (r_i + R_{TE}) / r_i \approx (f_0 / Q_A) \cdot [1 + (C_i / C_0) \cdot Q_E Q_A]$$

Thus the maximum filter bandwidth which can match the terminating impedance at minimum amplitude ripples is dependent not only on the parameters $L_i$, $C_i$, $C_0$ of the resonator but also on the quality factor $Q_E$ of the matching electric circuit. Estimations yield that minimum amplitude ripples caused by mismatching appear in a temperature interval if the condition $Q_E \le (0.1 - 0.2) Q_{AE}$ is met. In this case, with allowance made for capacity $C_A$ of the package, the maximum filter bandwidth is $BW_{\max} \le (Q_E \cdot f_0) \cdot C_i / (C_{0i} + C_A)$. For resonators on quartz in SMD packages one commonly has $C_i / C_{0i} \approx 0.068\%$ and $C_A \approx 3C_{0i}$. Taking the representative value $Q_E = 40$ as the quality factor of the external coil, we obtain $BW_{\max} \approx 0.28\%$ and $BW_{\max} \approx 0.6\%$ depending on whether the temperature effect is, or is not, taken into account, respectively. Both the values are substantially larger than the restriction put by acoustic coupling.

Thus, in TCRF with combined coupling, only the strength of acoustic coupling between resonators limits the maximum bandwidth.

## 3. EXPERIMENTAL RESULTS

The aforementioned factors limiting the maximum bandwidth of TCRF with different couplings between resonators have been tested experimentally.

Fig.5 shows the frequency response |S21| of a 360 MHz filter with bandwidth $BW$ =232 kHz (0.064%) at –3dB level. The filter involved two sections. Each section included two acoustically coupled resonators. No additional coupling elements were used and the shape of |S21| deviated from ideal Butterworth's function. The bandwidth was expanded as compared with the limit 0.0556% by means of adjusting the coupling coefficient.

Other filter that involved two pairs of resonators with combined coupling was on 402 MHz (Fig.6) and had $BW$ =490 kHz (0.122%) which is close to the maximum value $BW_4$ =0.125% achievable without using external coils. The expansion of bandwidth was due to optimization of the normalized coupling coefficients.

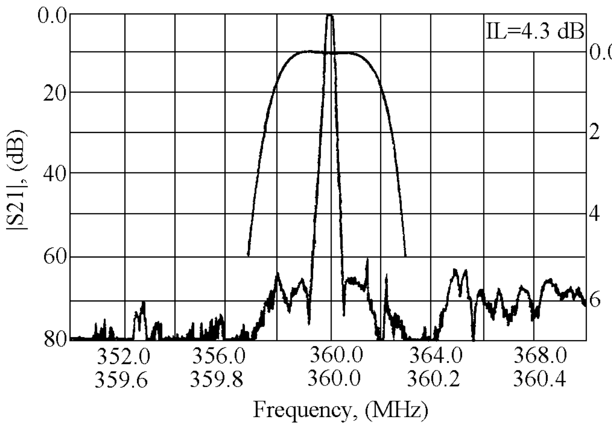


*Fig.5. Frequency responses $|S21|$ of 360 MHz filter with acousto-electric coupling of four resonators, $BW$ =0.064%*

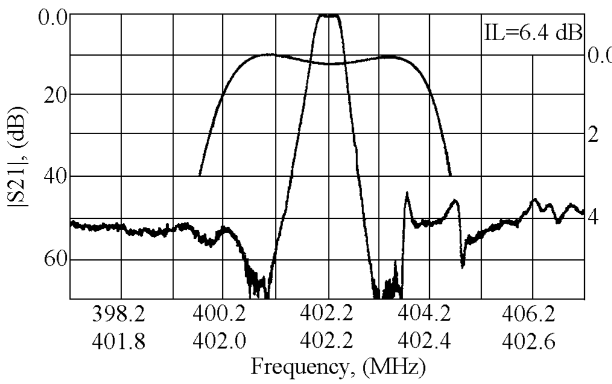


*Fig.6. Frequency responses $|S21|$ of 402 MHz filter with acousto-electric coupling of four resonators, $BW$ =0.122%*

The 315 MHz filter involved three purely acoustically coupled resonators (Fig.7) and had $BW$ =881 kHz (0.28%). This bandwidth is nearly equal to the theoretical limit 0.285 % for triple-resonator structures matched with inductors of $Q_E$ =18.

Finally, Fig.8 shows the frequency response $|S21|$ of a 244 MHz filter with four purely acoustically coupled resonators. The bandwidth was equal to $BW$ =352 kHz (0.16%). Its restriction was due to the necessity of suppressing spurious resonances to -40 dB and stronger.

## 4. CONCLUSION

Given Butterworth's transfer function, the maximum bandwidth of TCRF involving two acoustically coupled resonators on quartz can be $BW_2 / f_0$ =0.35% at the spacing $\delta = \lambda_0 / 4$ and is controlled by the feasibility of photolithography. The largest bandwidth $BW_3$ =0.494%

can be obtained in triple-resonator TCRFs with pure acoustic coupling. The bandwidths $BW_4$ =0.483% and $BW_5$ =0.478% can be achieved in TCRFs with purely acoustically coupled four- and five-resonator structures, respectively. Spurious resonances in the stop band reduce the real bandwidth approximately by factor about 2.

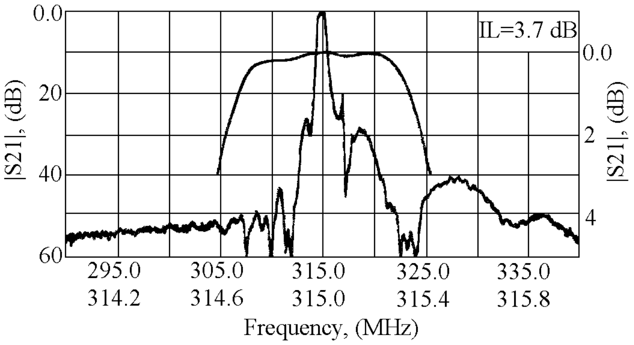


*Fig.7. Frequency responses* $|S21|$ *of 315 MHz filter with pure acoustic coupling of three resonators,* $BW$ *=0.28%*

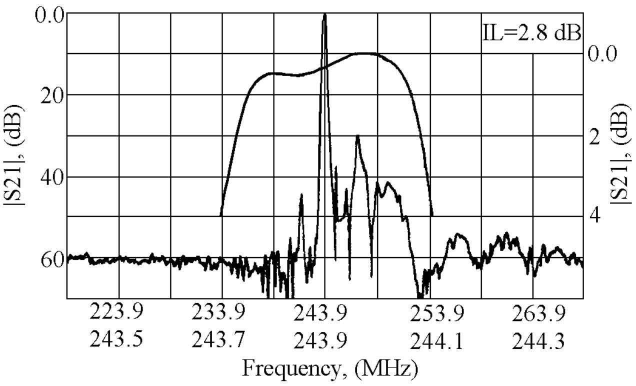


*Fig.8. Frequency responses* $|S21|$ *of 244 MHz filter with pure acoustic coupling of four resonators, BW=0.16%*

TCRF structures with combined coupling of four resonators without additional elements of electric connection allow the realization of the bandwidths $BW_4$ =0.0556% and $BW_4$ =0.125% for ideal Butterworth's function and quasi Butterworth's function with optimized coupling coefficients $K_{ij}$, respectively. The use of external coil allows the bandwidth expansion of four-resonator TCRF to $BW_4$ =0.317% and $BW_4$ =0.493% for Butterworth's and quasi Butterworth's functions, respectively.

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