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DESIGN OF NARROW-BAND TRANSVERSELY COUPLED AND BALANCED BRIDGE RESONATOR FILTERS USING EQUIVALENT CIRCUIT AND P-MATRIX MODELS

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Abstract – This paper reports on two methods of designing narrow-band resonator filters: the modified equivalent circuit model for transversely coupled resonator filters and modified P-matrix model for balanced bridge resonator filters. To raise the accuracy of simulation on the basis of both the models, we use the experimental parameters obtained for the two-resonator structure of the filter being designed or for individual resonators of the filter. The experimental data and theoretical predictions agree well for the yxl/33.3^o quartz filters with central frequency 86.8 MHz and band width 56 kHz.

1. INTRODUCTION

For simulation of SAW transversely coupled resonator filters (TCRF) the wave guide model [1] is commonly used. The procedure requires accurate data on SAW velocities on free, shorted surfaces and under grating structures, and the parabolic coefficients for velocity approximation. In practice, the simulated response obtained using the wave guide model agrees well with an experimental one only if the wave guide mode parameters are measured for special test structures [2,3]. The coupled resonators in TCRF often have different electrode periods for the frequency response in the pass band to be smooth. In this case the wave guide modes are no longer independent and the computation process becomes complicated [1]. We suggest another way of simulating TCRF. It is based on the modified equivalent circuit model free of the drawbacks mentioned above.

To avoid complicated layout schemes and matching networks in balanced connection of TCRF, we propose to use balanced bridge resonator filter (BBRF). We have modified the P-matrix model [3] for the simulation of resonators of TCRF and BBRF to account for different mechanisms of losses.

2. SIMULATION AND MEASUREMENT OF TRANSVERSELY COUPLED RESONATOR FILTER

A one-port high-quality SAW resonator with the low level of spurious signals in the pass-band and stop-band is the main element of TCRF and BBRF.

The one-port SAW resonator in a general manner is a distributed wave guide structure. This structure emits SAW in four directions: the X and –X directions coinciding with the forward and reverse directions of SAW propagation and the Z and –Z direction perpendicular the direction of SAW propagation. The latter is due to incomplete concentration of the energy in the wave guide structure and diffraction effects.

Therefore, the SAW resonator can be modeled as a 5-port network. This 5-port network is obtained from well-known Mason-Smith's 3-port network equivalent scheme that includes one electric port 3-3 and two acoustic ports 1-1 and 2-2. One should add two extra acoustic ports 4-4 and 5-5 through which the SAW energy leaks in the Z and –Z directions, respectively (Fig. 1).

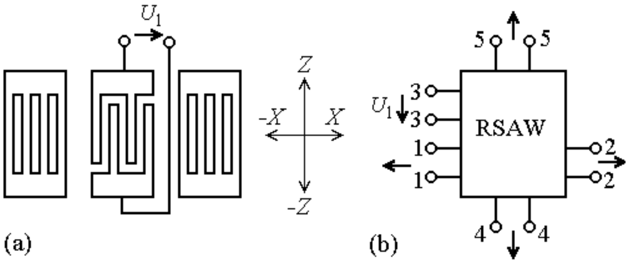

Fig.1. One port SAW resonator: a – structure, b – five-port network scheme

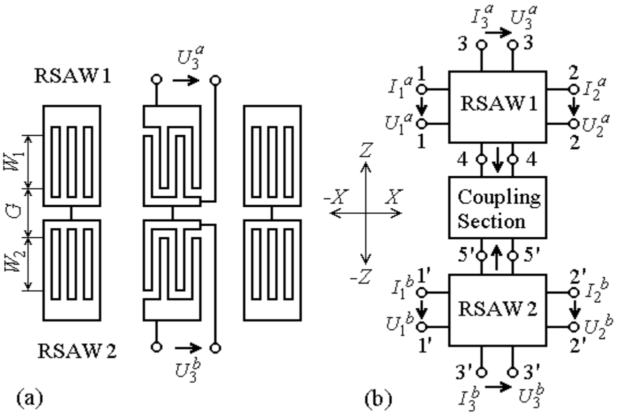

Fig.2. One cascade TCRF: a – structure, b – six-port network scheme

The simplest one-cascade TCRF is two SAW resonators 1 and 2 coupled in the Z direction (Fig. 2).

Let us neglect the energy leakage from resonator 1 in the Z direction and from resonator 2 in the –Z direction.

The one-cascade TCRF can then be modeled as 6-port network with internal connecting elements between resonators through extra ports 4-4 и 5'-5' (Fig.2). The transfer matrix for such a 6-port network is :

$$\begin{pmatrix} I_1{}^a \\ U_1{}^a \\ I_3{}^a \\ I_1{}^b \\ U_1{}^b \\ I_3{}^b \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} & c_{26} \\ c_{31} & c_{32} & c_{33} & c_{34} & c_{35} & c_{36} \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} & c_{46} \\ c_{51} & c_{52} & c_{53} & c_{54} & c_{55} & c_{56} \\ c_{61} & c_{62} & c_{63} & c_{64} & c_{65} & c_{66} \end{pmatrix} \times \begin{pmatrix} I_2{}^a \\ U_2{}^a \\ U_3{}^a \\ I_2{}^b \\ U_2{}^b \\ U_3{}^b \end{pmatrix}$$

The elements c_{ij} of this matrix involve the coupling coefficient $k_c = (k_{12}{}^2 \cdot k_{21}{}^2)^{1/2}$, describing the coupling of resonators through ports 4-4 и 5'-5'. Here k_{12} and k_{21} are the coefficients of coupling resonator 1 with resonator 2 in the directions $-Z$ and resonator 2 with resonator 1 in the direction Z respectively. The k_c value can be estimated by measuring the frequency characteristics of |S21| for the one cascade TCRF in the 50/50 Ohm tract.

To determine k_c one can simplify the equivalent scheme of one-cascade TCRF still more, reducing it to the equivalent scheme of two acoustically coupled piezoelectric BAW resonators [1]. If the coupling in such a system of two identical resonator exceeds the critical value yielding the appearance of two peaks at frequencies f_1 and f_2 in the pass band, then

$$k_c{}^2 = \frac{1}{Q_u{}^2} + 4\left(\frac{f_2 - f_1}{f_1 + f_2}\right)^2 \approx \frac{1}{\sqrt{2}} \cdot \frac{\text{BW3}}{f_0},$$

where f_1 and f_2 are frequencies of coupling measured in the mismatched 50 Ohm tract, Q_u is the loaded quality factor of the resonator, $f_0 \approx (f_2 + f_1)/2$ is the mean frequency of the filter, BW3 is the filter pass band on level –3 dB.

A series of experiments has been performed to determine the dependence of the coupling coefficient on the constructional parameters of TCRF (apertures W_1 and W_2 of resonators 1 and 2, the width G of the gap between these resonators, etc.). Each SAW resonator included N_T =131 electrodes in IDT and N_R =75 electrodes in each reflective grating (RG). The thickness of aluminum electrodes was 1.3 μ or h/λ =3.6%. The substrate was yxl/33.3° quartz cut. The electrode periods in IDT and RG have been chosen to be unlike, P_T / P_0 =0.99, in order to suppress spurious signals (longitudinal modes f [32] and f [31] according to M. Tonaka [1]).

Fig.3 shows k_c against W_1, W_2, and G . The wanted k_c value is estimated from the preset pass band of one cascade TCRF: $k_c \approx 0.7\text{BW3}/ f_0$. From Fig. 3 one sees that k_c decreases abruptly at G >1.2-1.5 λ . Therefore in following experiments we used G =1.25 λ . Increasing the resonators apertures to $W_1 = W_2$ =10 λ results in almost complete concentration of SAW energy in the wave guide structure. The leakage of SAW energy through ports 4-4 and 5'-5' in the Z directions decreases and k_c goes down (Fig.3b). The value k_c =0.045% brought about at $W_1 = W_2$ =7.92 λ secures the pass band of one filter section BW3=56 kHz. However, when $W_1 = W_2$, the coupling between resonators at frequencies of spurious signals of transversal modes f [13] и f [15] above the pass band is comparatively high (Fig.4a). To decrease this coupling the resonator apertures have been chosen to be unlike, W_1 / W_2 =7.92/7.0 (Fig.4b).

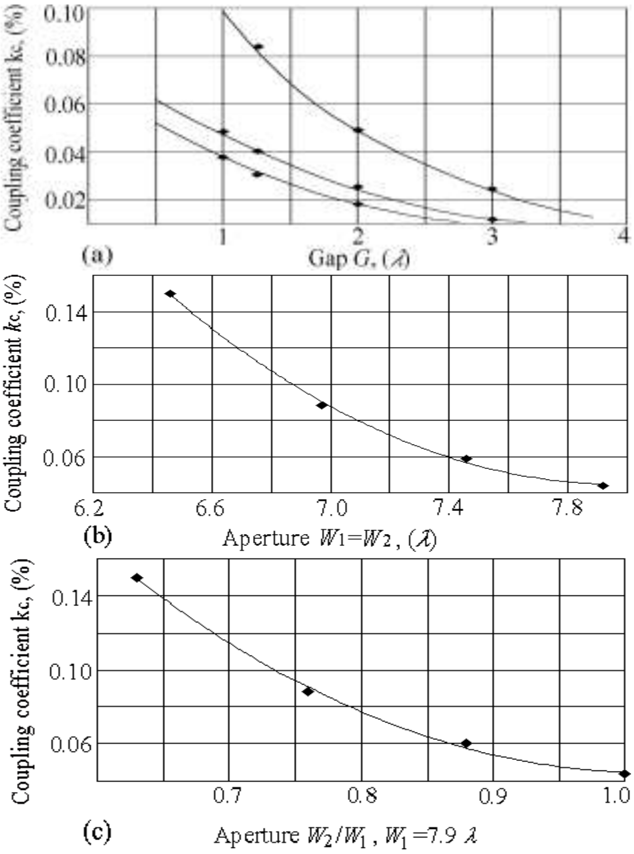

Fig.3. Dependence of coupling coefficient k_c on gap G between resonator (a) and apertures of resonators (b), (c)

To raise selectivity, one commonly uses two- or three-cascade TCRF with the electric coupling between internal resonators of cascades. The electric coupling shifts the frequencies of internal resonators and distorts the frequency response in the pass band. A modified model of equivalent circuits was used for the calculation and following refinement of resonator frequencies. The design of two-cascade TCR filter at central frequency 86.8 MHz for communication system AMPS-CD exemplifies the practical use of this model. The filter has been fabricated on yxl/33.3° quartz in package SMD 7.0x5.0x1.6 mm. The number of electrodes in each IDT and RG was N_T =131 and N_R=90, the electrode thickness $h/\lambda \approx$3.6%, metalization ratio 0.75. The frequency responses of the filter in the 50 Ohm matched tract are given in Fig.5. The pass bands of the filter were BW3=56.8 kHz and BW40=163.5 kHz, insertion loss was IL=3.8 dB, selectivity about UR=70 dB.

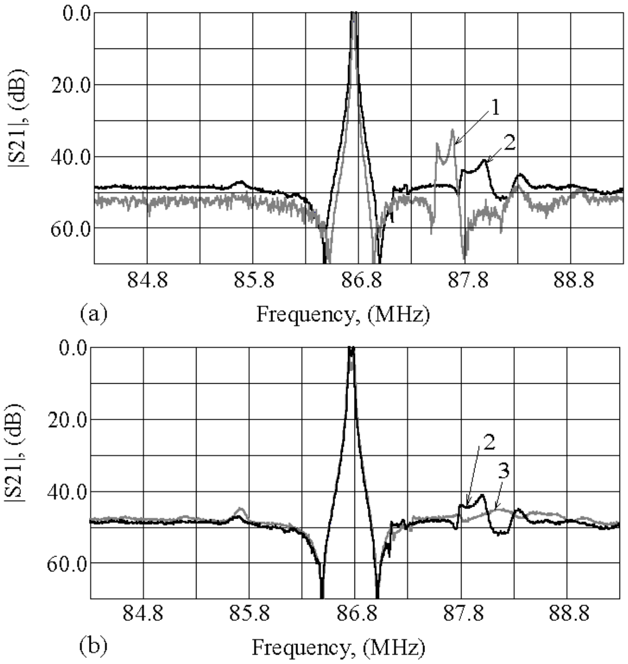

Fig.4. Frequency dependence of |S21| for one cascade TCRF: a – $W_1 = W_2$,b – $W_1 > W_2$ (1 - $W_1 = W_2 = 10\lambda$, 2 - $W_1 = W_2 = 7.9\lambda$; 3 - $W_1 / W_2 = 7.9/7.0$)

3. SIMULATION AND MEASUREMENT OF BALANCED BRIDGE RESONATOR FILTER

The equivalent scheme model is useful for the analysis of SAW resonators and filters with due regard for second-order effects. However, this model appears to be involved for synthesis. For the purpose of synthesis, models using fairly simple analytical relations between layout and electrical parameters of a device are more appropriate.

Such relations for computing frequency characteristics of uniform reflector and transducer gratings have been derived in D . Morgan's version of P -matrix model [3,6]. The transducer conductance has been estimated as the power of emitted wave at unit current. The susceptance has been evaluated using Hilbert transformation. However, Morgan's model does not take into account resistive loss, propagation loss, bulk wave conversion loss, etc. As a result, the relation between the transducer conductance and the power of the emitted wave becomes ambiguous, making the analysis of LSAW and STW devices to be inadequate.

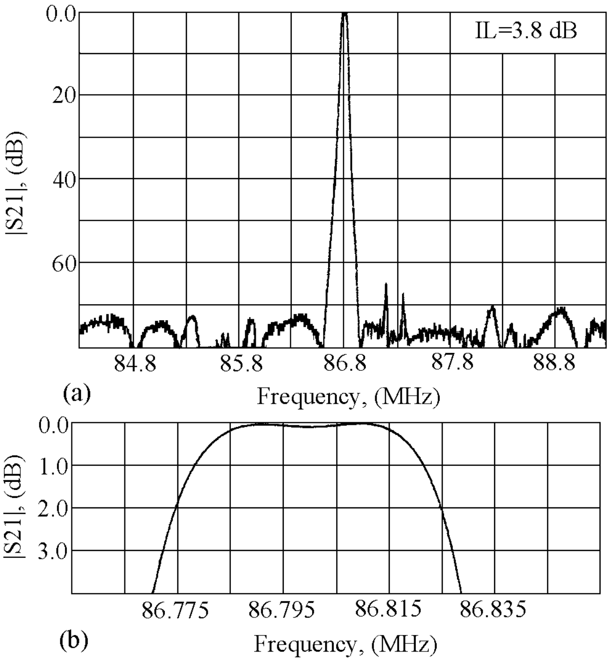

Fig.5. Measured frequency responses |S21| of two cascade TCRF

We have generalized Morgan's model [3,4] to account for loss. Let the amount of loss at each reflection from an electrode be proportional to the amplitude of waves incident on this electrode. Then $|r^2| + |t^2| + d^2 = 1$, where r , t , and d are the reflection, conversion, and scattering coefficients, respectively. With allowance made for loss, the dispersion equation becomes

$$\cos \gamma p = (1 - d^2)/t^* + 1/t ,$$

where γ is the wave number for the infinite grating, the symbol (*) signifies complex conjugation.

On the basis of this equation, we have derived analytical relation for computing the coefficients of the transfer matrix $\lfloor T_{ij} \rfloor$ of uniform reflector and transducer gratings. For the computation of the frequency responses of IDT, including the frequency dependence of the conductance and susceptance, one conventionally uses currents I_n and voltage V_n across electrodes. However, V_n are commonly determined to a constant C and I_n are fixed only on electrodes. The use of these quantities proves to be inconvenient. It appears more appropriate to employ voltage between adjacent electrodes $U_n = V_{n+1} - V_n$ and the increment of current $J_n - J_{n+1} = I_n$. The connection between U_n and J_n is determined via harmonic admittance $y(s)$ [5].

Summing up, we have obtained simple analytical expressions for computing characteristics of uniform reflector and transducer gratings. The IDT conductance has been evaluated without using Hilbert transformation and the connection with the power of emitted waves.

The model proposed preserves all the advantages of the P -matrix model [2,3] and makes computations substantially less labor-consuming. This is of special importance for the synthesis of devices.

The modified P -matrix model has been applied to the synthesis of one-port SAW resonators used both in the above-described TCRF and BBRF with the central frequency 86.8 MHz and the pass band BW3=56 kHz.

Fig. 6 shows the frequency characteristics of |S21| for this SAW resonator. The resonator characteristics computed using modified models of equivalent schemes and P -matrix agree well with experimental findings (Fig.6).

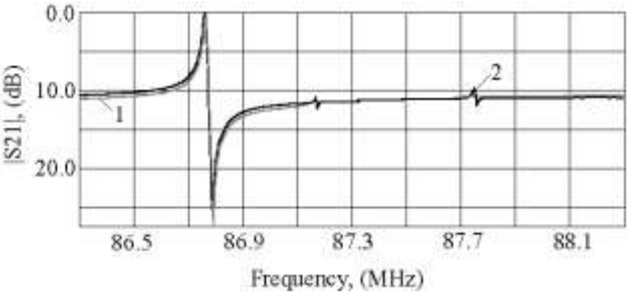

Fig.6. Frequency responses of one-port resonator 1 - simulated using two models, 2 - measured

For the balanced connection of TCRF one commonly creates involved schemes of resonator connections [6]. To simplify the filter structure we propose to use the balanced-bridge scheme each arm of which includes one-port SAW resonator and the elementary section is formed of a two-cascade TCRF. Fig.7 gives the frequency characteristics of |S21| for the BBRF at 86.8 MHz and BW3=56 kHz. The frequency characteristics of the TCRF (Fig.3) and BBR filter (Fig.7) created on the basis of alike resonators are nearly identical in the pass band. However, the matching scheme that uses balanced loads is simpler and the selectivity (about 75 dB) is higher for the BBRF.

CONCLUSION

We have shown that a one-cascade TCRF can be described by 6-port network equivalent scheme with internal coupling elements between resonators. The value of the coupling coefficient can be found using measurements of characteristics of one-cascade TCRF.

For the modified P -matrix model we have derived simple analytical relations that interrelate layout and frequency characteristics of reflector and transducer gratings with due regard for loss. The P -matrix model is useful for the synthesis of resonators. Both the modified model (equivalent schemes and P -matrix) have been utilized to compute small-size TCR and BBR filters for frequency 86.8 MHz with the pass BW3=56 kHz and selectivity about 70 dB.

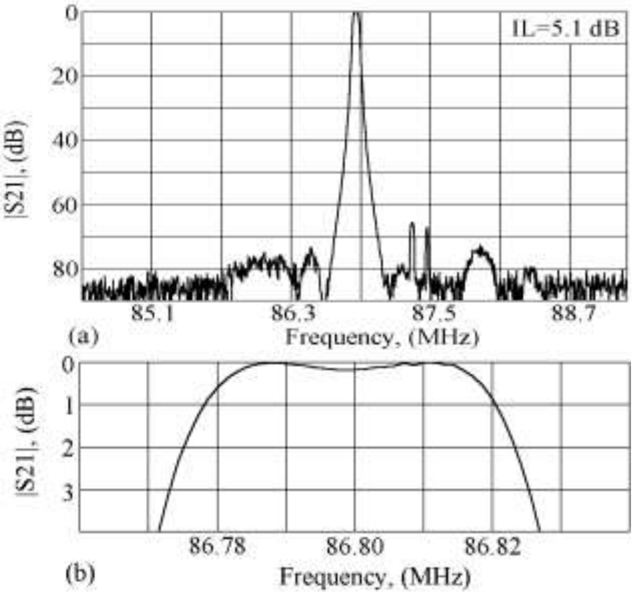

Fig.7. Frequency responses of two cascade BBRF

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