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DESIGN OF SAW LADDER FILTERS WITH UNEQUAL INPUT AND OUTPUT IMPEDANCES

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Abstract - **We propose to employ asymmetrical and symmetrical ladder resonator sections in the design of single ended and balanced filters with unequal input and output impedances. Three methods have been shown to be useful for designing such filters: 1) Mismatching of end sections and unequal loads, 2) jumping and 3) smooth change of impedances at the borders of adjoining sections. Theoretical estimations are confirmed by measurements for a number of filters, namely, 435 MHz , 607 MHz,, and 516 MHz filters with single ended loads and 770 MHz filter with balanced loads.**

Keywords - ladder filter; voltage standing wave reflection coefficients; coefficient of impedance transformation.

I. INTRODUCTION

Modern communication systems often require SAW filters operating between a source and a load whose resistances R_S and R_L are unequal. In these cases the necessary coefficient of transformation between input Z_{in} and output Z_{out} impedances of the filter matched to such loads can range from $K_{TF} = Z_{out}/Z_{in}$ = 75 Ohm / 50 Ohm=1.5 to K_{TF} = 200 Ohm / 50 Ohm = 4 and more. For instance, the antenna output impedance in front-ended devices usually equals 50 Ohm while the amplifier input impedance can equal 100-250 Ohm at single ended or balanced connections.

In SAW filters, 3DMS or 5DMS sections of longitudinally coupled resonators are commonly used for impedance transformation [1]. However, DMS filters cannot secure the shape factor better than *SH* = *BW40/BW3* =2.2-2.5. Besides, when utilizing DMS filters with impedance transformation, one meets some problems. First, distortions grow with decreasing IDT apertures. Second, insertion loss increases with K_{TF}.

In this paper we propose to use asymmetrical [2,3] and symmetrical [4] ladder resonator sections for the creation of single ended and balanced SAW filters with unequal input Z_{in} and output Z_{out} impedances.

We show that three methods of building such filters can be used: 1) Mismatching of identical end sections and unequal loads R_S and R_L, 2) jumping and 3) smooth change of the impedances Z_{in} and Z_{out} at the borders of adjoining non-identical ladder sections.

We have computed frequency responses both single and several (from *N*=1 to *N*=5) cascade-connected Π- type and *T*-type sections with equal $Z_{in}=Z_{out}$ and unequal $Z_{in}<Z_{out}$ input and output impedances. Further, we investigated the dependence of the filter main parameters (pass-band width *BW1* at level –1 dB , insertion loss *IL* , amplitude ripples *AR* at edges of pass-band *BW1*, voltage standing wave reflection coefficients at the central frequency $VSWR_0$ and $VSWR_{0.7}$ within commonly used 70 % interval of *BW1*, deviation $DSWR=VSWR_{max}-VSWR_{min}$ within this interval) on the coefficient of impedance transformation K_{TF} at different number of sections *N*. It has been shown that ladder *T*-type sections suit best of all for the impedance transformation. Given *VSWR*, the maximum of the transformation coefficient is achieved when the impedances of the connected sections change smoothly. Theoretical results have been checked experimentally for several types of multi-section ladder filters containing Π- type and *T*-type sections.

II. INVESTIGATION OF SINGLE LADDER SECTIONS

When the impedances of a ladder filter are mismatched with the external loads R_S and R_L, all filter parameters change in the pass-band. The most sensitive to the loads is *VSWR*. For this reason *VSWR* has been chosen as a criterion to compare different types of ladder sections. The frequency responses of Π- type and *T*-type single sections have been studied well enough [3,4]. These responses resemble each other in the pass-band but are different in the stop-band (Fig.1) [3,4]. In view of this fact, for correctness, we compared Π- type and *T*-type sections with equal relative pass-band widths *BW1* at the level of –1 dB (*BW1*=13.3 MHz at the central frequency about 524 MHz) and equal attenuation in the stop band (about -18 dB). Besides, structural parameters of the resonators in the sections have been chosen to provide $VSWR_{0.7}$ less than 1.05-1.1 within commonly used frequency range $F_0 \pm 0.35BW1$ (70% of passband width $BW1$). For this purpose, the input R_{in} and output R_{out} resistances in the pass-band of the section must approximately equal the load resistances R_S and R_L while the reactances X_{in} and X_{out} of sections must nearly vanish.

First we studied the frequency responses of standard single sections with equal input and output impedances ranging from $Z_{in}=Z_{out}$=50 Ohm to $Z_{in}=Z_{out}$ =250 Ohm and matched to the pure resistive loads $R_S=R_L$. The slop of the frequency dependences of *S21* and *VSWR* is flatter at the low-frequency edge for *T*- type and at the high-frequency edge for *П*-type sections (Fig. 1) because of the significant changes in the resistance of the corresponding sections in these intervals. Therefore these parts of the frequency responses will be more sensitive to changing loads and temperature, technological faults, etc.

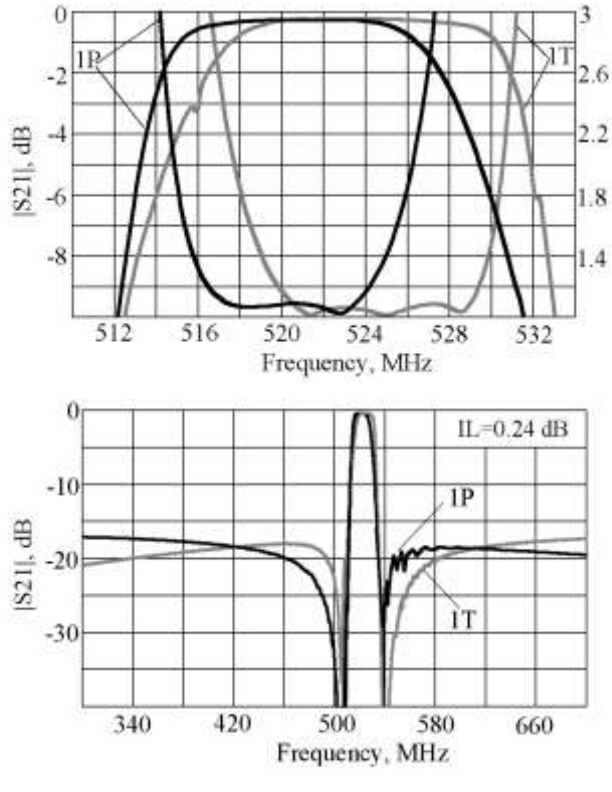

Fig.1. Simulated responses of simple T- and П-type 50/50 Ohm sections

Our analysis reveals that the insertion loss *IL* of both the *П*-type and *T*-type matched sections remains approximately equal when the impedances $Z_{in}=Z_{out}$ increase. *VSWR* corresponding to the frequencies at the edges of the pass-band *BW1* at a level of –1 dB is equal to 2,5-2,8. At the same time for both the types of sections the pass-band *BW1* and the frequency interval *BWR1.2* inside the pass-band, where *VSWR*=1.2 is achievable, relatively sharply decrease with increasing impedances from 100 to 250 Ohm. Here and further we evaluate the amplitude ripples *AR* in analyzed section or filter as attenuation at the edged frequencies 517 MHz and 530 MHz of pass-band *BW1* of single *T*-type section 50/50 Ohm. So for such single matched section *AR* is equal –1dB and is changed for other cases .

Next we studied the effect of the mismatching coefficient $K_L=R_{out}/R_L$ with external purely resistive loads ranging from R_L= 50 Ohm to 250 Ohm of the above standard single sections. As we expected, high-resistance *П* -type and *T* -type sections ($R_{in}= R_{out}=$ 100-250 Ohm) are more sensitive to variation of external loads than low-resistance sections ($R_{in}=R_{out}$=50-75 Ohm). The insertion loss *IL* and the amplitude ripples *AR* of high-resistance sections grow faster with increasing the mismatching coefficient $K_L=R_{out}/R_L$. The interval inside the pass-band, where one can get acceptable *VSWR*, narrows faster with increasing the section impedances $R_{in}=R_{out}$. More significant distortions of the responses have been observed on the flat parts of *S21*.

The comparison shows that the frequency responses depend on impedance transformation coefficient K_{TF} nearly equally for the *П*- type and *T*-type sections. However, *T*-type sections are more stable to the change of load, since the dependences of *BW1* and *AR* on mismatching K_L for these sections are weaker and allow one to achieve somewhat smaller distortions in the pass-band. Therefore, in what follows we give the results only for *T*-type sections.

III. INVESTIGATION OF MULTI- SECTION FILTERS

A. Cascade connection of identical sections

As the basis for comparison, we investigated ladder filters containing cascade-connected (from *N*=1 to *N*=5) identical *T*-type sections having $Z_{in}= Z_{out}$=50 Ohm without impedance transformation $K_T= R_{in}/ R_S= R_{out}/R_L$=1, i.e., when the end sections (the first and the last) match the loads $R_S=R_L$. With increasing the number of sections in such a filter, the attenuation in the stop band and insertion loss increase from *UR*=18 dB to 86 dB and from *IL*=0.24 dB to 1.2 dB. But the passband width is getting narrow from *BW1*=13.3 MHz to 11.7 MHz. The widest band *BW1*=14 MHz occurs when *N*=2, but in this case $VSWR_{0.7}$ is the worst and equals

$VSWR_{0.7}$=1.8-2.2 within 70% *BW1*, and *VSWR* at the low edge 517.3 MHz of pass-band *BW1* increases to 2.6-3.2. When the number of sections increases, $VSWR_{0.7}$ goes down to 1.6-1.8 (N=3) and to 1.4-1.6 (N=4) because of the influence of the non-zero reactances X_{in} and X_{out} of the cascaded sections. Usually $VSWR=R_S/|Z_{in}|$ at input of filter and $VSWR=|Z_{out}|/R_L$ at output of filter. So output *VSWR* is approximately equal to mismatching coefficient $K_L=R_{out}/R_L$ [5]. In current case $VSWR_0=|Z_{out}|/R_L$ at the central frequency changes from 1.04 (N=1) to 1.18 (N=4). The attenuation at the frequency 517.3 MHz corresponding to the low edge of the pass-band *BW1* of the base single section, abruptly increases with the number of sections from AR = 1.0 dB (N=1) to 4.5 dB (N=4).

As applied to multi-section filters containing identical sections, we have examined the possibility of the impedance transformation by merely mismatching R_{out} of the output section and purely resistive load $R_L > R_S$. Fig. 2 shows, for comparison, the main parameters of the filters containing N=1 and N =4 identical *T*-type sections with $|Z_{in}|=|Z_{out}|$=50 Ohm in each of them, as functions of the mismatching coefficient $K_L=R_{out}/R_L$ for the output section. The insertion loss *IL* and power loss *PL* of the filter connected between unequal resistive loads $R_S<R_L$ have been estimated using the formulas

$$IL=20\log E_S/U_L - 20\log[(R_S+R_L)/R_L],$$
$$PL=20\log E_S/U_L+10\log(R_L/4R_S)=$$
$$=IL+10\log[(R_S+R_L)2/4R_S R_L,$$

where E_S and U_L are the source voltage and the voltage at the filter load, respectively, R_S and R_L- are the source and load impedances, respectively. From Fig. 2 we infer that the pass-band dramatically decreases with increasing N and K_L, while the reflections and amplitude ripples grow abruptly ($BW1$=8.8 MHz , $VSWR_0$=4.0=K_L , $VSWR_{0.7}$=7.5, AR=3.5 dB for N=4). It can be seen, that the last values of $VSWR_{0.7}$ are more higher , than filter mismatching coefficient $K_L=R_L/R_S$=4.0.

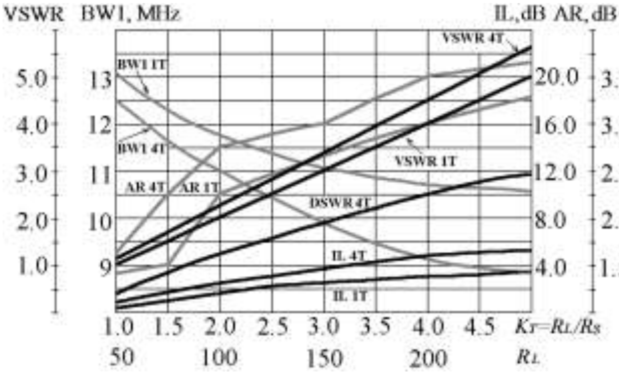

Fig.2. Parameters of filter with mismatched load RL

B. Cascade connection of non-identical sections

At the next stage we have investigated the impedance transformation in filters with jumping changes of impedances at the borders of connected sections. In order to determine the maximum of the impedance jump $K_T=|Z_{in}/Z_{out}|$ at the border of two adjoining sections, we estimated the frequency dependences of *S21*, Z_{in} and Z_{out} , *VSWR* of the filters constructed by connecting in cascade one section with $Z_{in}=Z_{out}$=50 Ohm or $Z_{in}=Z_{out}$=100 Ohm and another section with $Z_{in}=Z_{out}$ from 75 to 250 Ohm. According to our estimations, the maximum transformation coefficient for two sections must not exceed K_T = 1.5 in order to avoid distortions.

The input reflection coefficient of the filter created by connecting N sections in cascade equals

$$\Gamma_{inF}=\Gamma_1+\Gamma_2\exp(-i2\theta_1)+\Gamma_3\exp[-i2(\theta_1+\theta_2)]+\ldots+\Gamma_{N+1}\exp[-i2(\theta_1+\theta_2+\ldots+\theta_{N-1})],$$

where Γ_n is the reflection coefficient at the edge of connected sections and θ_n is the total phase shift of the *n*-th section. Since the reflection coefficient at the section input is $\Gamma_n=(Z_n-Z_{n-1})/(Z_n+Z_{n-1})$ and its magnitude is $|\Gamma_n|=(VSWR_n-1)/(VSWR_n+1)$ [5], the value of *VSWR* can be decreased as compared with $VSWR_0=K_L=R_L/R_S$ in multi-section filters, by changing the phase of Γ_n at the border of sections. However, one should choose $VSWR_0$ of a single section to be not more than 1.3-1.5 in order to avoid distortions of responses in the pass-band.

Fig. 3 shows the dependences of *IL*, *BW1*, *VSWR*, *AR* on the transformation coefficient for the filters created by connecting from N=1 to N=5 sections having $Z_{in}=Z_{out}$ and the jumping impedance change K_T=1.5 at each border of connected section from (50/50)+(75/75) Ohm to (50/50)+(75/75)+(100/100)+(150/150)+(200/200) Ohm. In the case of four *T*-type sections, the maximum transformation coefficient is K_{TF}=4 and $VSWR_F$=3.6 at F_0. The last value is lower than $VSWR_0=K_L=R_L/R_S$=4.0. Thus, given $VSWR_0$, the reactance part X_{in} of impedances of the cascaded ladder sections allows the maximum K_{TF} of the filter to be increased, in contrast to the case when the output section is mismatched with purely resistive load R_L.

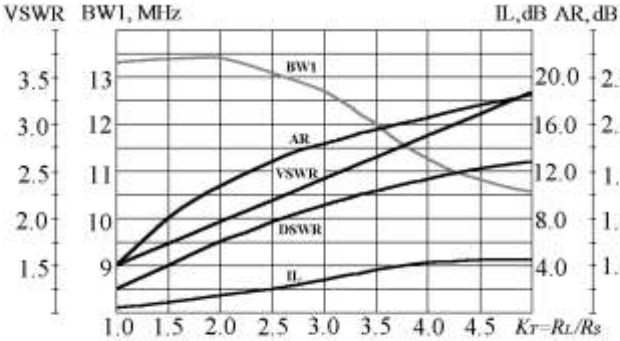

Fig.3. Parameters of filter with jumping impedance transformation

At the last stage the analysis have been performed of the frequency responses of the sections with unequal input and output impedances $Z_{in}<Z_{out}$. We have found out that the rate of smooth change of the impedances within a single section must be $Z_{out}/Z_{in} <$ 1.5 for distortions not to arise. Fig. 4 shows the dependences of *IL, BW1, VSWR, AR* of the filters constructed by connecting from N=1 to N=5 sections with Z_{out}/Z_{in}=1.5 in each section (impedances of sections from (50/75)+(75/112) Ohm to (50/75)+(75/112)+(112/169)+(169/250) Ohm). The maximum transformation coefficient is K_{TF}=4 at $VSWR_0$=3.5 for three *T*-type sections and K_{TF}=5 at $VSWR_0$=4.2. It can be seen, that these values are lower, than $VSWR_0$= $K_L=R_L/R_S$=5 for five *T* –type sections, mismatched with load.

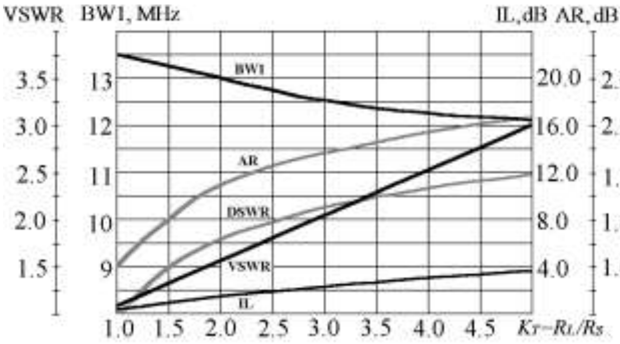

Fig.4. Parameters of filter with smooth impedance transformation

From Fig. 5 the following conclusion can be made. Given *VSWR*, the widest pass-band width *BW1*, of all cases considered (mismatching of the output section, connection of sections with jumping and smooth changes of the impedances), the smallest deviation of the amplitude of *AR* and *VSWR* in the pass-band, as well as the maximum transformation coefficient, are achieved when the impedances change smoothly at the borders of cascaded sections.

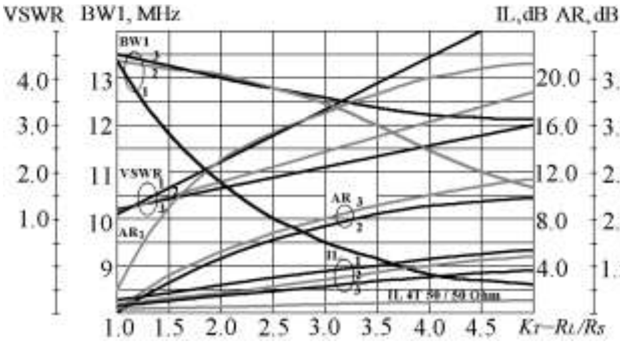

Fig.5. Comparison of filters parameters with different types of impedance transformation (1 – mismatching; 2 – jumping and 3 – smooth transformation)

IV. EXPERIMENTAL RESULTS

Theoretical estimations have been checked experimentally. Fig.6 shows the frequency responses of the 607 MHz filter with single ended impedances Z_{in}= Z_{out}= 50 Ohm. The filter consists of 3 *T*-type identical sections for comparison. The 435 MHz filter with single ended impedances Z_{in} = 50 Ohm and Z_{out} =100 Ohm consists of 3 *T*-type non-identical sections with jumping impedance (Fig.7). The 516 MHz filter with single ended Z_{in}=50 Ohm and Z_{out}=150 Ohm consists of 4 *T*-type sections with smoothly changing impedances (Fig.8). The 770 MHz filter with impedances Z_{in}=150 Ohm balanced and Z_{out}=250 Ohm balanced involves 4 *Π*-type mismatched sections (Fig.9). In all these cases the theoretical and experimental results are in good agreement.

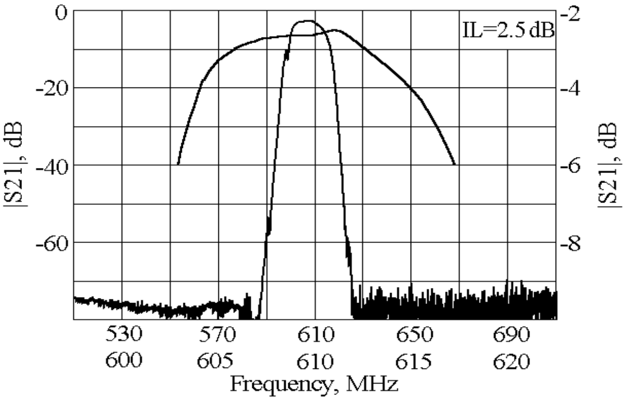

Fig.6. Measured responses of 607 MHz filter with 3 T-type identical 50/50 Ohm sections, $R_S=R_L$=50 Ohm

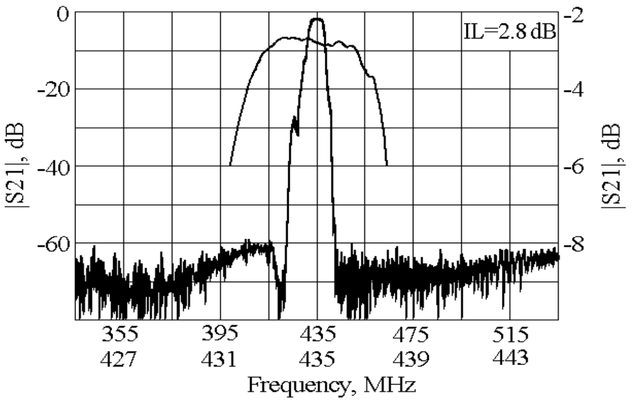

Fig.7. Measured responses of 435 MHz filter with 3 T-type sections (50/50)+ (71/71)+(100/100) Ohm, R_S=50 Ohm, R_L=100 Ohm

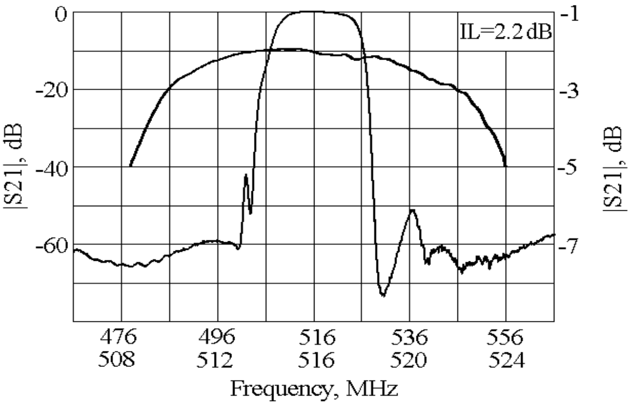

Fig.8. Measured responses of 516 MHz filter with 4 T-type sections (50/60)+ (60/72)+(72/85)+(85/100) Ohm, R_S=50 Ohm, R_L=100 Ohm

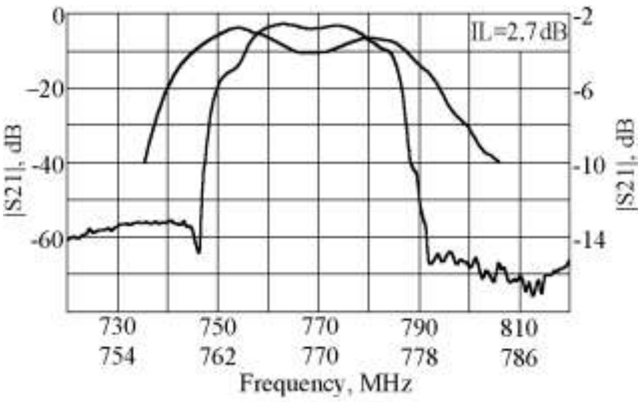

Fig.9. Measured responses of 770 MHz filter with 4 Π - type sections, Z_{in}=150 Ohm, Z_{out} =250 Ohm balanced, R_S=R_L=250 Ohm balanced

CONCLUSION

Multi-section ladder filters with unequal input and output impedances can be designed on the basis of the following principles: 1) Connection of identical sections, the output section is mismatched with the load; 2) connection of section featuring jumping impedances at the borders of sections; 3) connection of sections with smoothly changing impedances at the borders of sections. According to our results, one obtains the widest pass-band and the smallest deviation of the amplitude of *AR* and *VSWR* in the pass-band, when the section impedances change smoothly.

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