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SAW FILTERS WITH COMBINED SINGLE-MODE AND DOUBLE-MODE SECTIONS

S.V.Kiselev, E.I.Fedorov and V.S.Orlov,
Moscow Radiocommunication Research Institute,
Nizhegorodskaya str., 32, Moscow, 109029, Russia

Abstract – In this paper, we discuss low-loss SAW filters composed as a combination of ladder or balanced bridge single-mode one-port resonator section (LDR or BBR) and double-mode longitudinally coupled resonator (LCR) section. Such combinations of single-mode and double-mode sections allows the operation of IF or RF filters with single-ended or balanced loads 50-300 Ohm and insertion loss IL=2.3-3.8 dB without additional matching circuits. Besides, the ultimate rejection increases to UR=55-70 dB in a wide frequency range. The matching of unity sections has been studied in order to decrease distortions caused by reflections. The characteristics of SAW filters with LDR-LCR-LDR; LCR-LDR-LCR; LCR-BBR-LCR; LDR-BBR structures are reported, with center frequencies 442, 484, 135, 105 and 160 MHz, respectively.

1. INTRODUCTION

IF and RF SAW filters for modern communication systems must exhibit low insertion loss IL=0.8-3.5 dB and at least 50-60 dB ultimate rejection in the stop band. The same filter can be loaded by single-ended or balanced load in the range 50-300 Ohm, dependent on the type of communication equipment. There is no universal technical solution how to create a SAW filter meeting all these requirements. SAW filters with single-mode resonator sections, such as ladder (LDR) and balanced bridge (BBR) ones, provide the smallest insertion loss IL=0.8-1.5 dB. However, the typical ultimate rejection of LDR filters is UR=25-30 dB [1] and the shape factor of BBR filters is only $SH(40/3)$=3.5-4.0 [2]. The filters composed of the sections of double-mode longitudinally coupled resonator (LCR) have the best ultimate rejection, which reaches UR=50-65 dB in a wide frequency range. The frequency response $|S21|$ of the unit section of an LCR filter has a "shoulder" at the level A_s=9-12 dB, which can be suppressed if the number of sections is increased, but it results in higher insertion loss [3]. Many efforts have been made to suppress the "shoulder" in LCR filters using either shunt capacitor [4] or extra reflector [5], but these efforts did not succeed in providing high ultimate rejection UR=50-60 dB in a wide frequency band. Besides, an additional increase of insertion loss was observed.

In the present paper, we describe a method of improving ultimate rejection of SAW filters. Our method uses the combination of single- and double-mode resonator sections: LCR-LDR-LCR; LCR-BBR-LCR; LCR-LDR; LDR-LCR-LDR; BBR-LDR-BBR, LDR-BBR. Utilizing of inner LDR and BBR section allows the suppression of the "shoulder" of LCR sections to A_s=45-55 dB. Outer LCR sections allow to use not only single but also balanced loads and exclude matching circuits. Moreover, LCR sections can transform the output filter impedance Z_{in}=50 Ohm into a different value in the range Z_{in}=50-300 Ohm.

Matching of different types of unit sections is the main difficulty of designing such combined filters, because imperfect matching results in increased insertion loss and distortions of the frequency response, especially at the edges of the pass band. In the paper, specific features of matching are described for single- and double-mode unit sections. Several examples of filters built as different combinations of such sections are reported.

Since the parameters of LDR filters in the radio frequency range are strongly dependent on the inductance and capacitance of bonding wires and packages, the intrinsic characteristics of combined filters have been analyzed at low frequencies 100-500 MHz.

2. PARAMETERS OF UNIT SINGLE- AND DOUBLE-MODE RESONATOR SECTIONS

2.1. Double-mode LCR unit sections

Single- and double-mode resonator sections have been extensively studied. We only review those properties that are important if a combination of different types of sections is utilized in the same filter structure. For the sake of proper comparison, the unit sections with approximately identical bandwidth $BW3$=2% have been designed on $yxl/42^o$ $LiTaO_3$ cut. The IDT apertures have been chosen to match 50 Ohm circuit load.

Figure 1 shows the frequency characteristics of amplitude $|S21|$, input R_{in}, X_{in} or output R_{out}, X_{out} resistances and reactances for some of section types at the load or source impedance $Z_L = Z_S$=50 Ohm.

Due to their universal properties LCR sections play a key role in combined filters. Estimations yield that the bandwidth of an LCR section with interaction between 1st and 3rd modes, or (1-3)LCR, is about 20% wider than that of an LCR section with interaction between 1st and 2nd modes, or (1-2)LCR; while insertion loss are 0.1-0.3 dB lower. In addition, the "shoulder" level A_s in a (1-3)LCR section depends more strongly on the electrode thickness. This fact can be used to increase A_s. The frequency dependence of the input resistance R_{in} and reactance X_{in} of two types of double-mode LCR sections are similar. The R_{in} and X_{in} values change by factor 3-4 in the bandwidth. R_{in} has two pronounced "peaks" whose location corresponds to the coupling frequencies of 1st and 3rd, or 1st and 2nd, modes. The reactance X_{in} has a positive peak at the high-frequency edge of the pass band. In the middle of the pass band, X_{in} is close to zero. R_{in} and X_{in} increase abruptly near the high-frequency edge of the pass band, X_{in} being positive (Fig.1a).

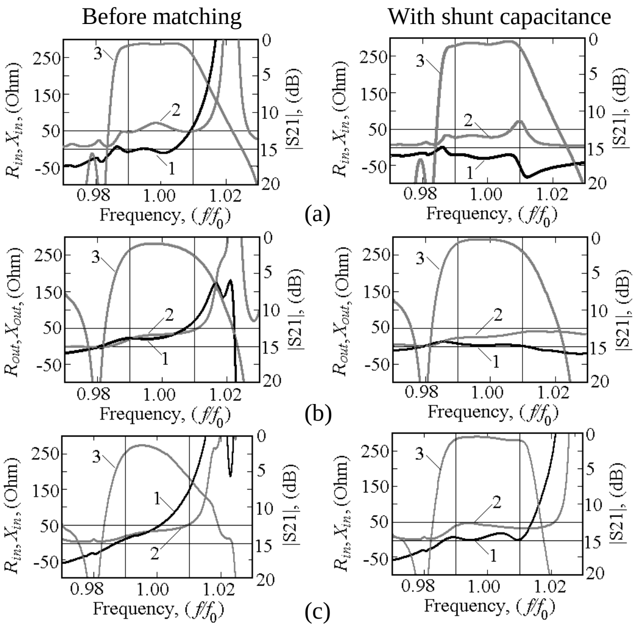

Fig.1. Frequency responses of unity sections before and after matching with shunt capacitance: a - (1-2)LCR; b- Γ -type LDR; c - T -type LDR (1- X_{in}, 2- R_{in}, 3-$|S21|$)

2.2. Ladder unit sections based on single-mode resonators.

The frequency dependence of R_{in} и X_{in} for ladder sections of Γ -type, T -type, π -type grows steadily in the pass band and rises sharply at the high-frequency edge of the pass band, with X_{in}>0. The frequency dependence of R_{in} и X_{in} is more gently sloping for T -type than for Γ -type sections, and for π -type sections R_{in} и X_{in} exhibit the flattest part in the pass band.

A Γ -type section has a high peak of R_{in} at the high-frequency edge of the pass band. Comparison of Fig.1b and Fig.1c reveals that the smallest variation of R_{in} at the pass-band edges occurs for T -type sections. Thus, T - and π -type sections are better suited for combined filters.

2.3. Balanced Bridge Unit Sections based on Single Mode Resonators

In a BBR section, the flattest R_{in} characteristic, which is close to 50 Ohm value within the largest part of the pass band, can be obtained. The X_{in} value varies around zero, increasing gently at the high-frequency edge of the pass band.

Comparison of the different types of elementary sections shows that the average impedance in the pass band depends on the type of section and varies within a wide range, though the frequency dependence of this characteristic looks similar for any type of section. In a combined filter, with different sections cascade connected, this makes difficult to reach optimal matching, that is simultaneously minimize insertion loss and distortions in the pass band.

3. MATCHING OF UNIT SECTIONS IN COMBINED FILTER

As is known from the theory of four-pole networks, the loss can be minimized if the impedances of the source and load are complex conjugate, i.e. $Z_S = Z_L^*$, while $Z_S = Z_L$ is required for minimum reflections [6], where $Z_S = R_S + jX_S$ and $Z_L = R_L + jX_L$ are complex source and load impedances, respectively. To reach a reasonable balance between the level of loss and reflection-caused distortions, one can "partial complex conjugate matching", which means that the reactances of source and load are divided into two portions, $X_S = X_{S1} + X_{S2}$ and $X_L = X_{L1} + X_{L2}$. The first portion is set approximately equal, i.e. $X_{S1} \approx X_{L1}$ within the whole pass band and for the second portion $X_{S2} \approx -X_{L2}$ at the edges of the pass band [7]. The source and load resistances are set approximately equal $R_S \approx R_L$ in the pass band. Thus, the distortions at the edges of the pass band are determined by the ratio between two portions of reactances X_{S1}/X_{S2}, X_{L1}/X_{L2} and between resistance and reactance in Z_L and Z_S. It is possible to change both Z_L and Z_S of adjacent sections by their internal matching in combined filter. As result, few iterations are usually enough to find optimal ratio between X_{S1}/X_{S2}; X_{L1}/X_{L2}; R_L/X_L; R_S/X_S for simultaneously minimize insertion loss and distortion.

According to estimations, "partial complex conjugate matching" is readily achievable if LCR is combined with T-type ladder section or BBR is combined with symmetric π-type section. In both cases the bandwidth of the LDR section must be 5-10% wider than that of LCR or BBR sections.

In filters involving LDR or LCR sections, in order to reduce distortions at the low frequency edge one can use an extra matching resonator with negative part of X_{in} at the low frequency edge [1]. The resonant frequency of this resonator is chosen to be lower than that of the resonator in the series-connected "shoulder" of Γ- or T-type sections.

To decrease distortions at the high-frequency edge of the pass band and to increase the suppression of the "shoulder" of the LCR-section, one can use a shunt capacitor in the parallel-connected arm of ladder Γ- or T-type sections. In this case, the transfer function S21 of the ladder section becomes non-symmetric and exhibits the attenuation increased by 8-12 dB near the high-frequency slope (Fig.1b). In addition, the shunt capacitor cancels out the positive growth of X_{in} and R_{in} at the high-frequency edge of the pass band of LDR and LCR sections, allowing the decrease of distortions caused by the mismatching of these sections.

To match the impedances of BBR and LCR sections, it is better to use the symmetric IDT in the LCR section. The implementation of symmetric π-type LDR sections with additional shunt capacitors decreases distortions of S21 at the pass-band edges in filters involving BBR and LCR sections. The shunt capacitors are manufactured as an IDT on the surface of the substrate.

4. RESULTS OF SIMULATION AND MEASUREMENTS

The above-described peculiarities of transfer functions and impedances of single- and double-mode unit sections have been implemented to decrease distortions, insertion loss, and improve ultimate rejection in combined filters of several types. Let us use a 442 MHz filter to illustrate the specific features of the combined-filter design.

The 442 MHz filter with $BW3$=2.2% and (Γ-LDR)-(1-2)LCR-(T-LDR) structure (Fig.2a) was simulated for 50/50 Ohm single-ended loads. To decrease the level of the "shoulder" in the (1-2)LCR section to A_s=48-52 dB, the transfer functions of Γ- and T-type LDR sections have been chosen non-symmetric (Fig.2b). To reduce distortions at the lower edge of the pass band caused by the mismatching of the section impedances, the resonant frequencies f_{s1} and f_{s2} of the series-connected resonators had been shifted as compared with their values in the initial LDR sections. The distortions at the upper edge had been reduced using shunt capacitors. The internal matching of sections expanded the bandwidth of the combined filter

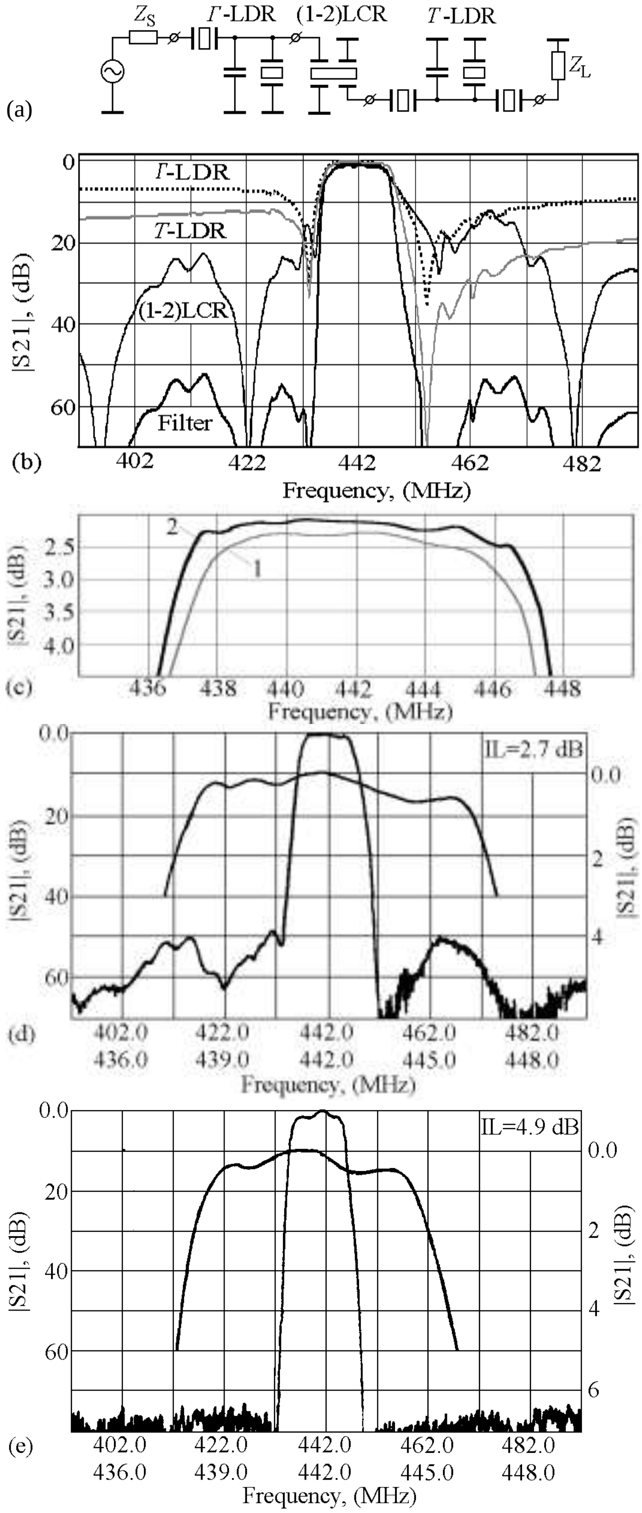

Fig.2. 442 MHz filter with structure (Γ-LDR)-(1-2)LCR-(T-LDR): a - scheme of filter; b - simulated |S21| of sections and filter; c - simulated |S21| of filter before (1) and after (2) internal matching of sections; d - measured responses |S21| of filter in narrow and medium frequency range; e - measured response |S21| of two cascade filter

by 0.8 MHz (12%) and decreased insertion loss by 0.3 dB (Fig.2c). The theoretical characteristics of LDR and LCR sections of the filter before and after matching are given in Fig. 1a,b,c. The theoretical and experimental results agree well (Fig.2b,d). The ultimate rejection is UR =50-55 dB near the pass band and goes up to 60 dB in a wide frequency band, insertion loss being IL =2.7 dB. The ultimate rejection grows to UR =75-76 dB if two filters are cascade-connected. In this instance, insertion loss increase to IL =4.9 dB (Fig.2e).

The 484 MHz (1-2)LCR-(2T-LDR)-(1-2)LCR filter with $BW3$ =1.7% (Fig.3a) was simulated both for single-ended and balanced loads. Series connection of the IDT parts of the (1-3)LCR section transforms the filter output impedance, e.g., from 50 Ohm into 200 Ohm. The use of two T-type LDR sections raised attenuation of the "shoulder" of the (1-3)LCR section to A_s =55 dB and resulted in ultimate rejection UR =60-65 dB in a wide frequency range at reasonable insertion loss IL =3.6 dB. With one T-type LDR section excluded in the 135 MHz filter with $BW3$ =2% and (1-2)LCR-(T-LDR)-(1-2)LCR

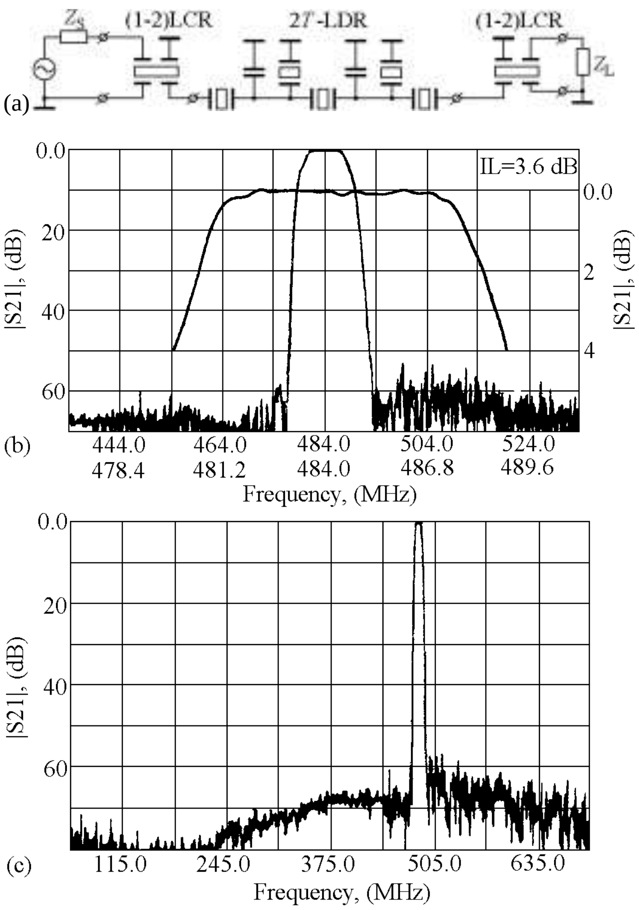

Fig.3. Filter 484 MHz with structure (1-2)LCR-(2 T -LDR)-(1-2)LCR: a - scheme of filter; b - measured |S21| in narrow and medium frequency range; c - measured |S21| in wide frequency range

structure, insertion loss was decreased to IL =2.9 dB while the ultimate rejection was around UR =57-65 dB (Fig.4).

Combined filters involving a balanced bridge section show the best ultimate rejection in a wide frequency range. For example, the 105 MHz filter with BW3=1.9% and (1-3)LCR-BBR-(1-3)LCR structure (Fig.5a) exhibited UR =65-70 dB and IL =3.4 dB (Fig.5b). This filter can be loaded both on 50/50 Ohm single-ended and 150/150 Ohm balanced loads. The main problem in designing filters with BBR sections is to obtain flat $|S21|$ response within the pass band.

A BBR section can also be combined with symmetric LDR sections of the π-type. The 160 MHz filter with $BW3$ =1.4% had (2π-LDR)-BBR structure and was intended to operate in a 200/200 Ohm balanced loads (Fig.6a). Replacing the input symmetric π-type LDR section by the T-type LDR section allows the operation with single-ended 50 Ohm source.

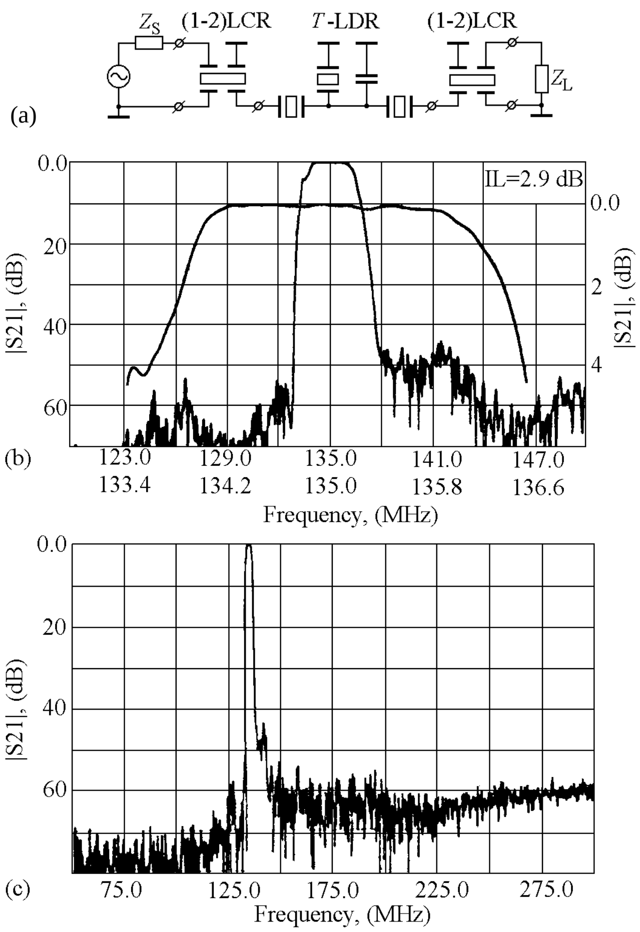

Fig.4. Filter 135 MHz with structure (1-2)LCR-(T -LDR)-(1-2)LCR: a - scheme of filter; b - measured |S21| in narrow and medium frequency range; c - measured |S21| in wide frequency range

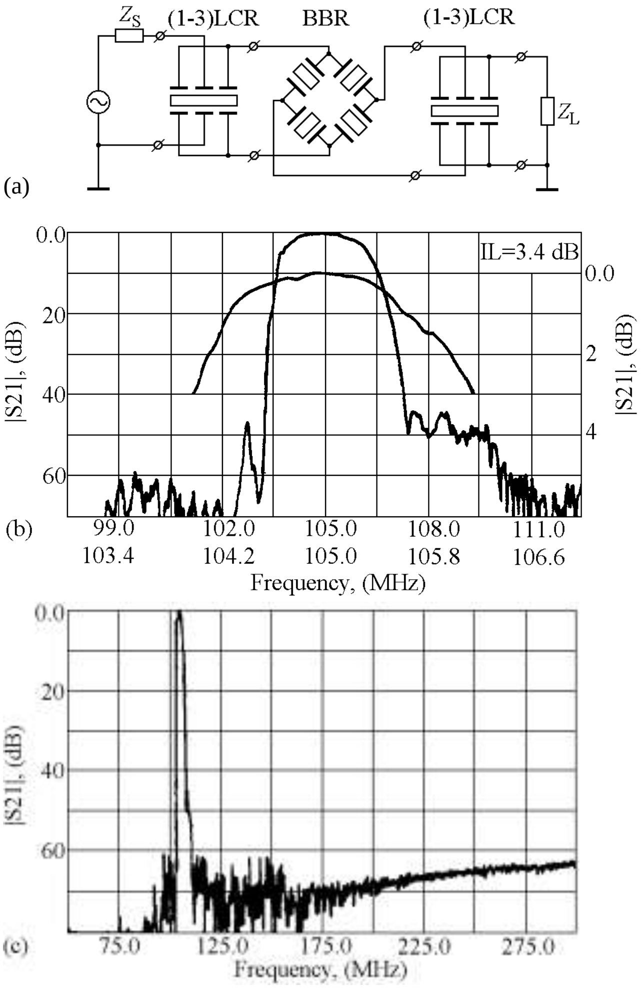

Fig.5. Filter 105 MHz with structure (1-3)LCR-BBR-(1-3)LCR: a - scheme of filter; b - measured |S21| in narrow and medium frequency range; c - measured |S21| in wide frequency range

Packages SMD 14.0x8.2x1.8 mm were used for 105 MHz and 135 MHz filters. Packages SMD 5.0x7.0 mm were used for 442 MHz and 484 MHz filter.

5. CONCLUSION

Combining single- and double-mode resonator sections results in increased number of degrees of freedom in designing IF and RF SAW filters and allows one to avoid the shortcomings of the unit sections of different types.

The LCR-LDR-LCR or LCR-BBR-LCR filters are suitable for operation with single-ended or balanced loads and can be used to transform the impedance from 50 Ohm into any value within the range 50-300 Ohm.

The combination of LDR or BBR sections allows improved attenuation of the "shoulder" of the LCR, up to 45-55 dB, and ultimate rejection *UR* =60-70 dB in a wide frequency range. The partial complex conjugate matching of unit sections can be used to decrease the reflection-caused distortions at the edges of the pass band, with fairly low insertion loss.

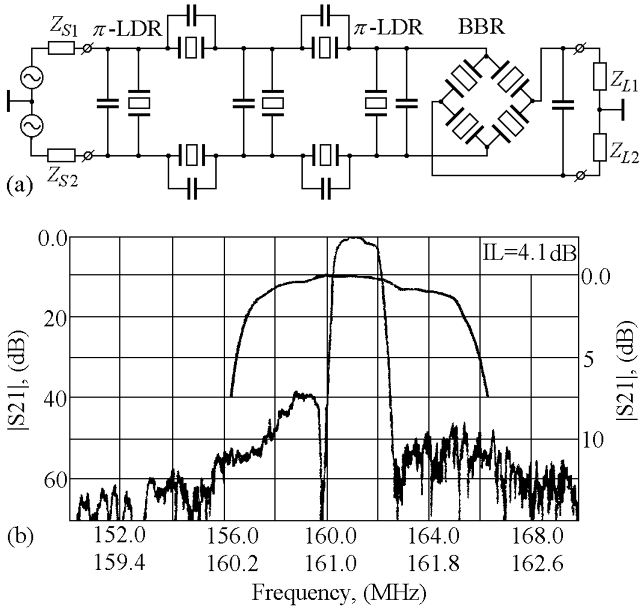

Fig.6. Filter 160 MHz with structure (2 π -LDR)-BBR: a - scheme of filter; b - measured |S21| in narrow and medium frequency range

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