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EXTREMELY LOW-LOSS SAW FILTER AND ITS APPLICATION TO ANTENNA DUPLEXER FOR THE 1.9 GHz PCS FULL-BAND

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Abstract- An antenna duplexer for the 1.9 GHz PCS-band handsets is realized by developing extremely low-loss and ultra-steep cut-off SAW filters. In this paper, design techniques to achieve the characteristics that satisfy all severe specifications required for the PCS-band duplexer is presented. Developed SAW duplexers have the insertion loss of –2.0 dB and –3.2 dB in the Tx and Rx band, respectively. Also, the attenuation levels are –53 dB and –45 dB. The device size is as small as 5x5x1.5 mm^3. These performances are sufficient for the PCS duplexer to be practical.

I. INTRODUCTION

The performance of SAW (Surface Acoustic Wave) filters used in mobile communication systems has progressed drastically in the last ten years[1]. Recently, the antenna duplexer using SAW filters, in which much lower insertion loss and higher power handling capability are required than inter-stage filters, has been developed[2]. The SAW filter technology seems to be well developed today. Nevertheless, demand still exists for higher-performance SAW filters with extremely low-loss, ultra-steep cut-off and high power durability. One application with demanding requirements is the PCS (Personal Communications Service) band duplexer. The PCS band is centered around 1.9 GHz, and the frequency gap between Tx and Rx band is only 20 MHz. When the TCF (Temperature Coefficient of Frequency) and productivity are taken into account, both the Tx and the Rx filters have to have the narrower transition band than 10 MHz. So far, the severity of this specification has been beyond the capability of conventional SAW filter technology.

This paper demonstrates a drastic improvement in SAW filter performance that makes SAW filters a practical choice for the PCS band duplexer. First, SAW energy loss in the resonator is reduced. Next, the design techniques are presented to obtain an ultra-steep cut-off and increased power handling capabilities in a ladder type SAW filter. And then the performance of a duplexer for the 1.9 GHz PCS full-band is shown. Finally, we compare SAW and FBAR (Film Bulk Acoustic Resonator) duplexers[3] and show you that SAW technology has advantage in the frequency range of 1.9 GHz.

II. REDUCTION OF SAW ENERGY LOSS IN THE RESONATOR

Our research group has succeeded in directly observing the leakage of shear-horizontal waves in a 1-port SAW resonator, shown in Fig.1, on 42YX-Cut $LiTaO_3$[4].

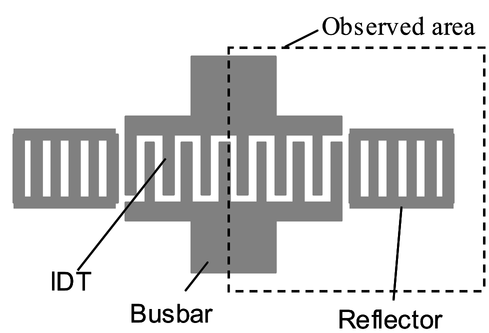

Fig.1 Structure of 1-port SAW resonator

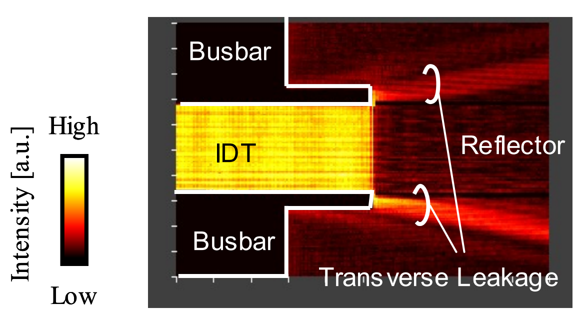

Fig.2 Observed leakage pattern

Fig.2 shows the observed leakage pattern. It is clearly observed that the SAW energy leaks in transverse direction from the IDT (InterDigital Transducer). This leakage has been a main cause of the large insertion loss in the SAW resonator.

In order to reduce the insertion loss, the transverse leakage was analyzed with respect to the waveguide condition of the IDT. The waveguide condition on 42YX-Cut $LiTaO_3$ is that the V_g should be faster than V_b[5]. Here, V_g and V_b are the velocity in the IDT and in the busbar, respectively. Fig.3 shows the calculated velocity relation between V_g and V_b for the 1.9 GHz filter. V_g exhibits the frequency dispersion due to the Bragg reflection and the resonant point of the resonator is located at the minimum velocity. On the other hand, V_b is constant for frequency. These calculations show that SAW leakage occurs in the frequency around the resonant point. From the corresponding resonator response shown in Fig.3, it is found that the SAW leakage causes an increase in insertion loss and a poorer cut-off characteristic.

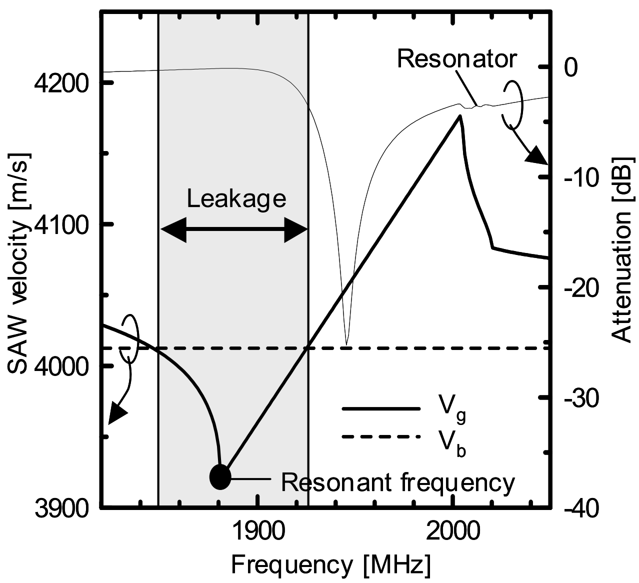

Fig.3 Calculated SAW velocity and resonator response

Based on above analysis, we propose an IDT structure with metallization-ratio smaller than 50% shown in Fig.4, although conventional SAW filters employ the IDT with metallization-ratio around 50%. Fig.5 shows the calculated V_g for several metallization-ratios. The frequency range for the leakage becomes much smaller for the 30% metallization-ratio than 50%, but SAW still leaks near the resonant frequency. For the 20% metallization-ratio, V_g becomes faster than V_b in the every frequency range. These calculations indicate that the insertion loss can be reduced using the IDT structure with smaller metallization-ratio than 50%.

$$\text{Metallization-ratio} = \frac{L}{L+S}\ [\%]$$

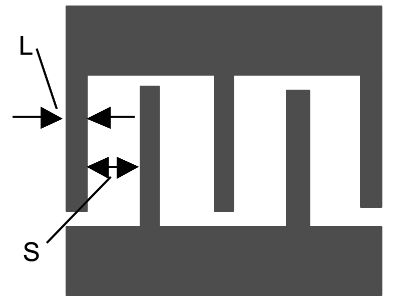

Fig.4 IDT structure with smaller metallization-ratio

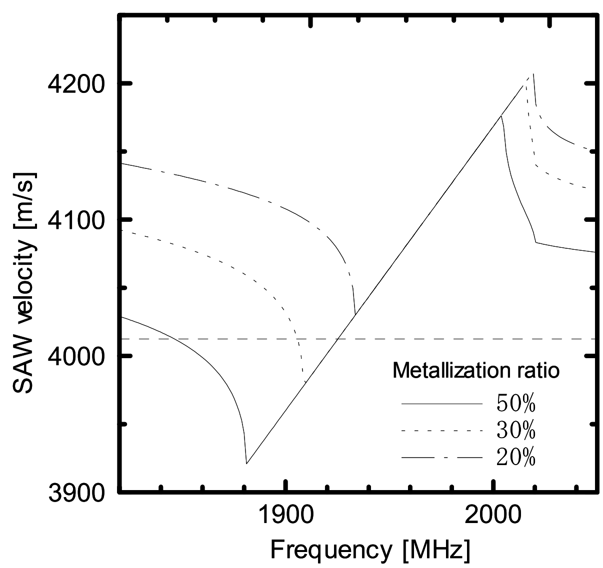

Fig.5 Calculated SAW velocities for several metallization-ratios

Based on these calculations and taking the fabrication process and the resistance of the IDT into consideration, 4-stage ladder type SAW filter was fabricated with a 35% metallization-ratio for a Tx filter in the PCS band. Here, only the metallizaion-ratio in the series-arm resonators was reduced to 35%. Fig.6 shows the frequency response. The insertion loss around the higher passband edge reduced and a steeper cut-off was obtained. The transition band from –3.5dB passband to –42 dB stopband narrowed to as little as 15 MHz.

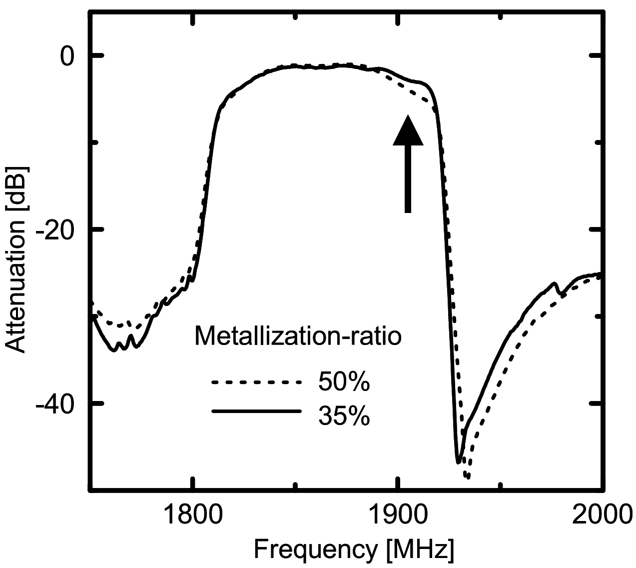

Fig.6 Frequency response using IDT with a 35% metallization-ratio

III. DESIGN TECHNIQUE FOR ULTRA-STEEP CUT-OFF CHARACTERISTICS

In this section, the design technique to reduce the transition band of the ladder type SAW filter from 15 MHz to less than 10 MHz is present, in order to fulfill the specifications of the PCS band duplexer.

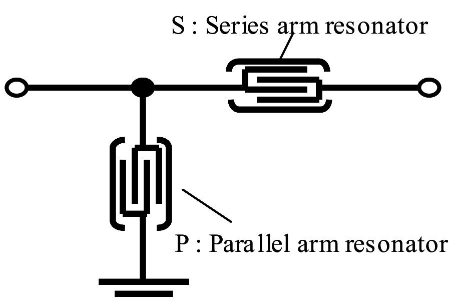

Fig.7 1-stage ladder type filter

First, let us discuss the cut-off characteristic of the 1-stage ladder type SAW filter shown in Fig.7, which is the basic unit, by using the admittance of each resonator. Fig.8 shows the calculated filter response and the admittances of series and parallel arm resonators. Here, we investigate the cut-off on the higher frequency side for the Tx filter. It is clear that the pole of the filter response is coincident with the anti-resonant frequency f_a of the series arm resonator. Also, the edge of the passband is approximately coincident with the intersection f_b of the admittance of the series and parallel arm resonators, because at the higher frequency than f_b, the electric current flows to the parallel arm because of the lager admittance. This means that the stopband has formed. On the lower frequency side than f_b, the electric current flows to the series arm resonator. This means that the passband has formed. So, the area around the intersection becomes the edge of the passband. It can therefore be concluded that the cut-off is determined by the frequency difference f_a-f_b between the intersection and the anti-resonance of the series-arm resonator.

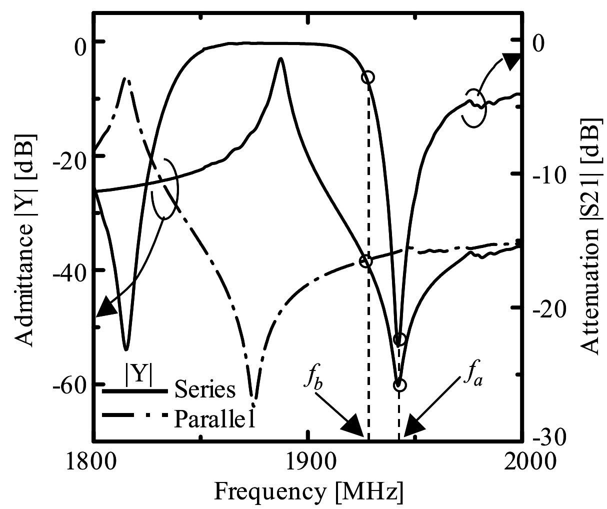

Fig.8 Admittance and filter response of 1-stage ladder type SAW filter

Next, the cut-off characteristic of the 4-stage ladder type filter shown in Fig.9 is investigated for the actual Tx filter. A conventional technique for steeper cut-off is to shift the resonant frequency of some series resonators.

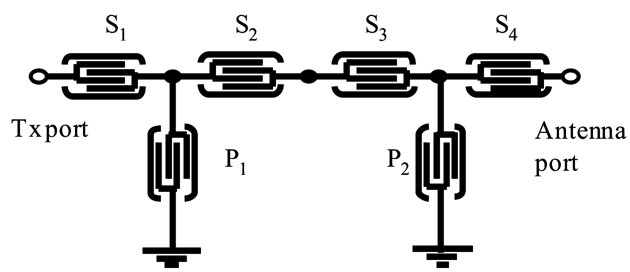

Fig.9 4-stage ladder type SAW filter

In Fig.10, the thin lines show the calculated filter response and the admittance in case that all series arm resonators have the same resonant frequency and the thick lines show the calculated filter response and the admittance in case that the resonant frequency of two series resonators are shifted to a lower frequency by

0.4 %. The cut-off characteristic becomes steeper for the thick line because the new pole appeared at a lower frequency. Now, we can use the admittances in considering this improvement. First, the new pole results from the shifted anti-resonance indicated by the white circle. Next, observe that the intersection is split, as indicated by the black circles, because of the frequency shift. This means that the edge of the passband has become less sharp. Actually, the insertion loss increased slightly around the passband edge. It can therefore be concluded that the ultra-steep cut-off cannot be obtained using only the frequency shift technique.

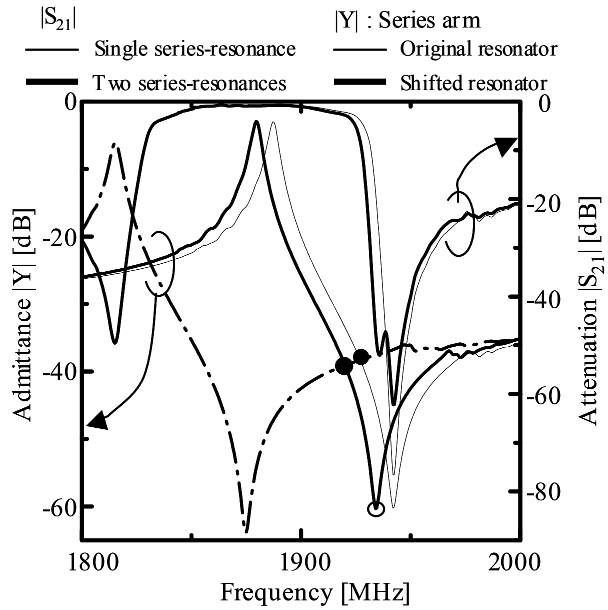

Fig.10 Frequency response in case that two series resonators were shifted to a lower frequency.

The authors propose a reduction in the electromechanical coupling coefficient K^2 for only selected series resonators. In Fig.11, the thick solid lines show the filter response using frequency shift technique and the admittance of the shifted resonator shown in Fig.10. Here, only the anti-resonance of the shifted resonator was moved to a lower frequency without any change of the admittance around the intersection as indicated by the dashed line. For this admittance, the value of K^2 was reduced by 2%. Furthermore, the static capacitance was also increased by 20% to keep the admittance around the intersection original curve. The calculated filter response is also shown in Fig.11 by the dashed line. The pole moved to a lower frequency without any increase in insertion loss around the passband edge. From these calculations, it can therefore be concluded that a much steeper cut-off can be obtained with reduced K^2 of selected resonator.

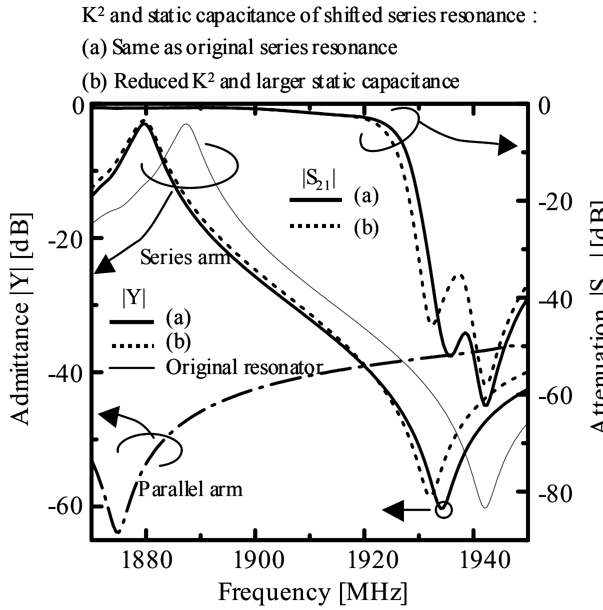

Fig.11 Frequency responses with reduced K^2

A PCS-Tx filter was fabricated using the above design technique on 42YX-Cut $LiTaO_3$. Fig.12 shows the frequency response. The solid line is the optimized frequency response. The dashed line, shown for comparison purpose, is the response when only the frequency shift technique was used. The optimized response has a lower insertion loss at the higher passband edge and a steeper cut-off characteristic. A transition band as narrow as 8 MHz was obtained. These performances are sufficient for a PCS duplexer application.

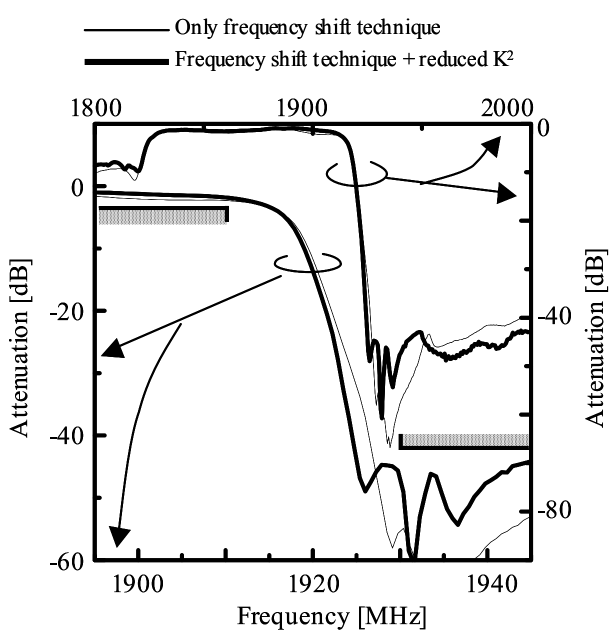

Fig.12 Frequency response of fabricated PCS-Tx filter

IV. DESIGN TECHNIQUE FOR HIGH POWER HANDLING CAPABILITY

It is known that the power durability of a ladder type SAW filter exhibits a strong frequency dependence and the weakest point exists in the transition band[6]. For the PCS-Tx filter, the transition band narrowed to 8 MHz, as mentioned in the previous section. Therefore, the weakest point approaches closer to the passband, and this means that the PCS-Tx filter may have poorer power durability compared with the conventional designs. In this section, the power durability of the PCS-Tx filter is improved by adjusting the filter design.

First, the absorbed power in each resonator was calculated to understand the frequency dependence of the power durability. For the calculation of the absorbed power, the voltage source was connected to the Tx port, and the antenna port was terminated with the load of 50 Ω in the 4-stage ladder type filter shown in Fig.9. Also, each resonator response was represented by the admittance calculated using the coupling of modes theory[7]. Here, the IDT period λ was set to 2.12 μm for every series resonator. Fig.13 shows the calculated absorbed power. It is noticed that a large peak exists in the transition band for the first series resonator S_1 and this peak is much larger than those in other resonators. These calculations suggest that only the first series resonator S_1 degrades rapidly when the input power is applied around the passband edge and this leads to poorer power durability.

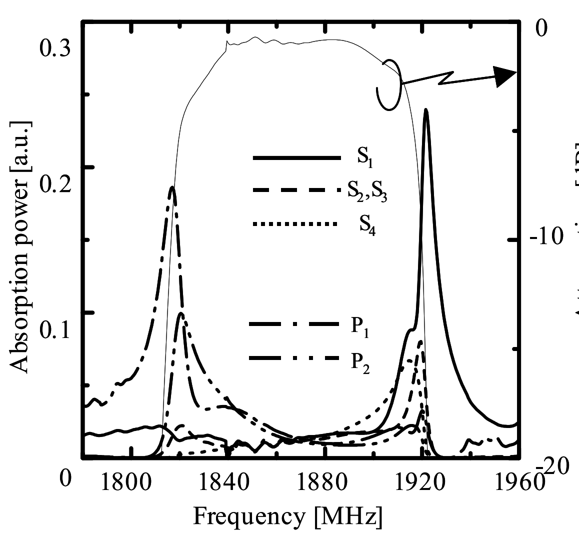

Fig.13 Absorbed power in each resonator

In order to improve the power durability, the design technique to reduce the peak power in S_1 was investigated. Fig.14 shows the change of absorbed power in S_1 when the IDT period λs_1, that is the frequency of S_1, has shifted. It was found that the peak power level becomes smaller as $\Delta\lambda s_1 = \lambda s_1 - \lambda$ increases. It is also noted that when $\Delta\lambda s_1$ is 0.008 μm, a novel peak appears in the passband, therefore, $\Delta\lambda s_1$ should be less than 0.008 μm.

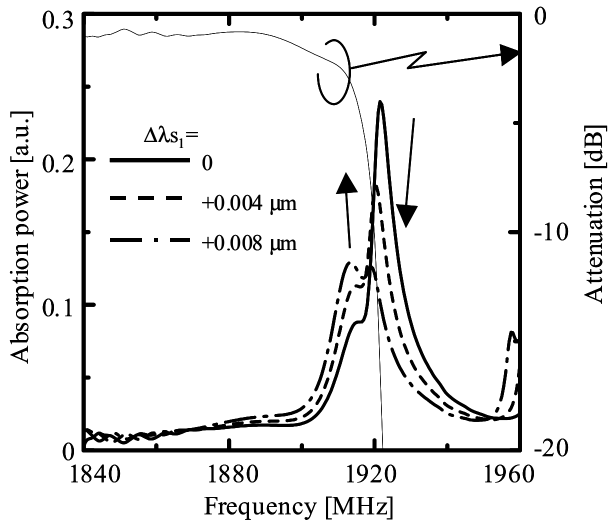

Fig.14 Change of absorbed power in S_1

The basic experiment was performed using Al-Cu electrode technology to verify the above calculations. Fig.15 shows the evaluated lifetime of the PCS-Tx filter.

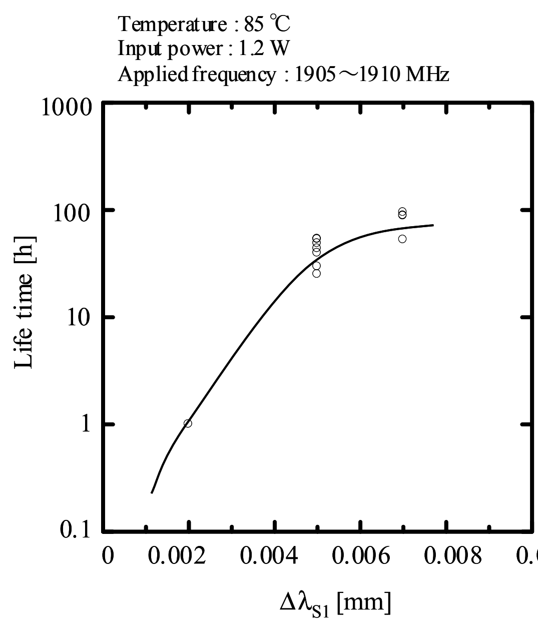

Fig.15 Evaluated lifetime using Al-Cu electrode

The atmospheric temperature was 85 deg.C, and a continuous wave of 1.2W was applied in the frequency range from 1905 to 1910 MHz. This frequency range is the weakest point of the PCS-Tx filter. Although the IDT in S_1 broke down immediately for $\Delta\lambda s_1=0$, the lifetime was approximately 100 hours for $\Delta\lambda s_1=0.007$ µm. For a larger $\Delta\lambda s_1$ than 0.007 µm, there seemed to be no significant improvement. So, $\Delta\lambda s_1=0.007$ is sufficient value to improve the power durability using this design technique. These experimental results verified the dependence of power durability.

V. SAW DUPLEXER PERFORMANCE AND COMPARISON WITH FBAR DUPLEXER

Duplexers were fabricated using re-optimized SAW filters with ultra-steep cut-off and high power durability. Both Tx and Rx filters were mounted in a 5x5 mm^2 ceramic package with strip line for impedance matching. Fig.16 shows the duplexer response.

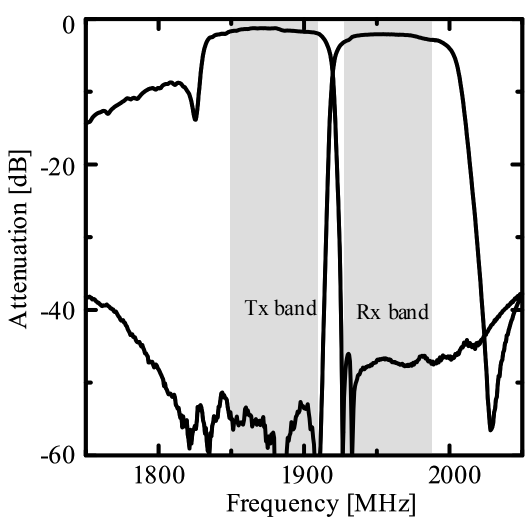

Fig.16 Performance of fabricated SAW duplexer

The insertion loss in the Tx band is –2.0 dB, and in the Rx band it is –3.2 dB. The attenuation levels were –53 dB and –45 dB, in the Tx and Rx band, respectively. Fig.17 shows the Tx to Rx isolation. Obtained attenuations were –55 dB and –50 dB. These performances are sufficient for the PCS duplexer to be practical.

Now, let us compare the fabricated SAW duplexer and the FBAR duplexer[8]. As shown in Fig.18, for the Tx filter, the SAW duplexer has a steeper cut-off characteristic and better attenuation level. For the Rx filter, SAW and FBAR duplexers are in a same level. Furthermore, the comparison with PCS-Tx single filters is provided in Fig. 19, in order to evaluate the low-loss characteristic of SAW filter technology[9]. The insertion losses were also in the same level. From these comparison and taking into consideration the fabrication process, we are convinced that the SAW technology has the advantage in the 1.9 GHz frequency range over the FBAR technology.

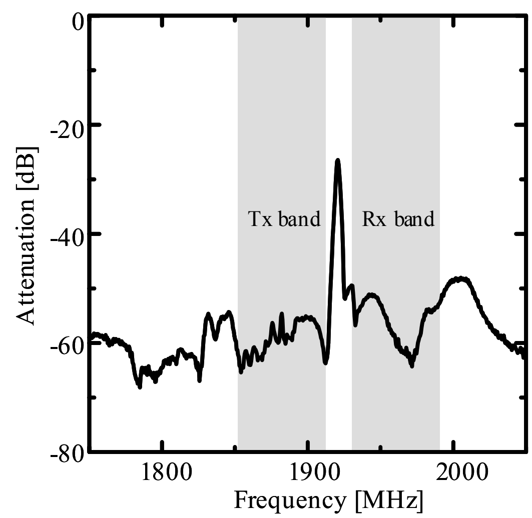

Fig.17 Tx－Rx isolation

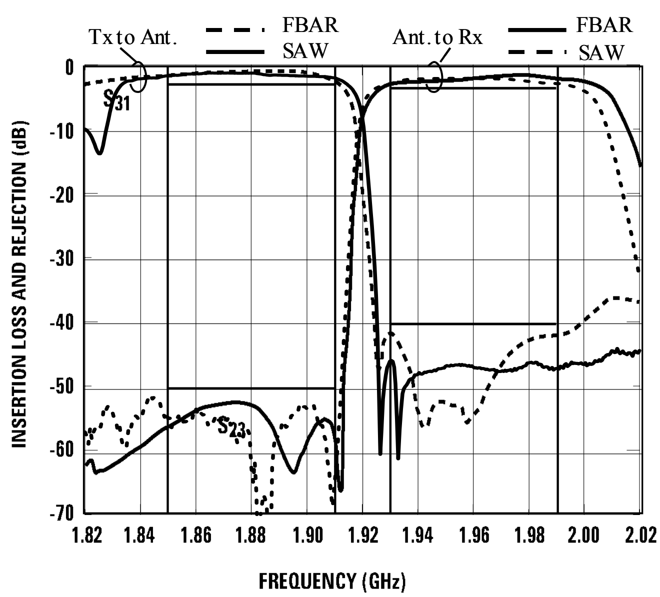

Fig.18 Comparison between SAW and FBAR duplexers

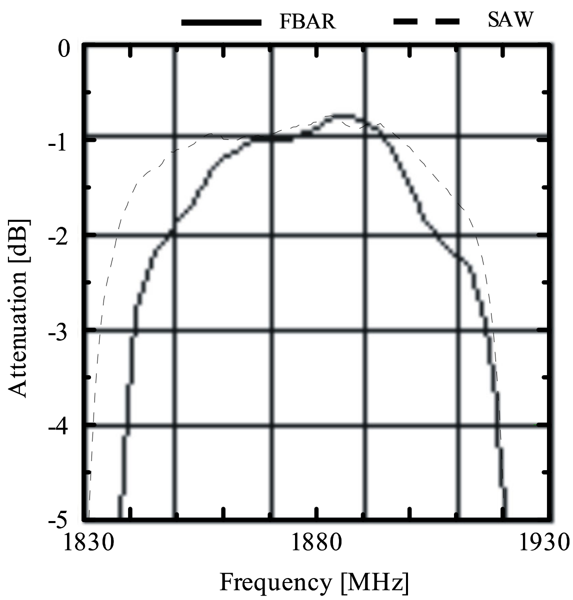

Fig.19 Comparison of PCS-Tx filter

VI. CONCLUCION

We have developed an extremely low-loss, ultra-steep cut-off ladder type SAW filter. In the SAW filter we developed, each SAW resonator has smaller metallization ratio and is optimized for frequency shifting and K^2. In addition, the SAW resonators have been optimized for high power durability. Using these technologies, we have succeeded to develop for the first time an antenna duplexer for PCS full-band that incorporates SAW technology.

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