

RF SAW Filters

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Abstract - This paper describes the recent technology of RF SAW filter's development relating to cellular phone applications. The description of the filter design is focused on the ladder type SAW filter as an example of RF SAW filter with low-loss and wide band characteristics. First of all, the feature of ladder type SAW filter design is described comparing with other filter designs such as DMS and IIDT. The substrate crystals and fabrication process for high frequency SAW filters and their applications to the GHz range SAW filters are also described. The power durability of SAW filters is also important for RF application. The recent technology for high power durability and its application to antenna duplexer are described. Finally, the future trend of these technologies is summarized.

INTRODUCTION

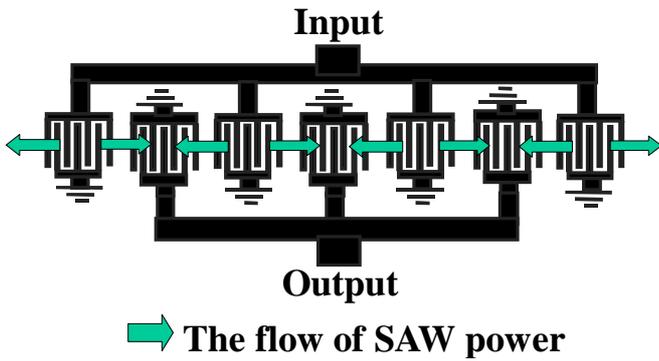
The recent remarkable progress of cellular phones has made us possible not only to speak at every-time, everywhere, and with everybody, but also to access into the internet wherever we go. The sharp cut-off characteristics and miniaturization of RF filters and IF filters by using SAW technologies have made important role to improve the performance and the size of cellular phones. SAW devices are now key devices for cellular phones and other mobile communication products with small and thin size. The productions of RF and IF SAW filters are growing up year by year according to the growth of the cellular market. The specifications and the technologies used are very different from each

other between IF and RF SAW filters. In this paper, the development of SAW filter focussing RF application is described in detail.

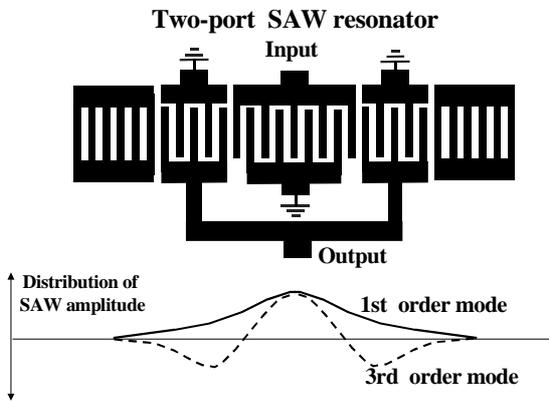
The recent cellular phone systems have required the higher operating frequency and the wider bandwidth to RF SAW filters in order to realize the high quality and the high data rate of mobile communication. For the RF SAW filters, three kinds of IDT (Inter-Digital Transducer) design method have been proposed so far. Those are an IIDT (Inter-digitated Inter-digital Transducer) design, a ladder-type SAW filter design and a DMS (Double Mode SAW) design. In this paper, we focus on the ladder-type SAW filters because the ladder type SAW filter is the most suitable design method for the high frequency and wide-band requirement. We describe the feature of it comparing other design. In addition, the piezoelectric substrate suitable to new these IDT design and the fabrication process for high frequency SAW filters, the power durability, and the antenna duplexer as the present stage of development. We finally discuss the future trend of SAW filters.

FEATURES OF A LADDER TYPE SAW FILTER

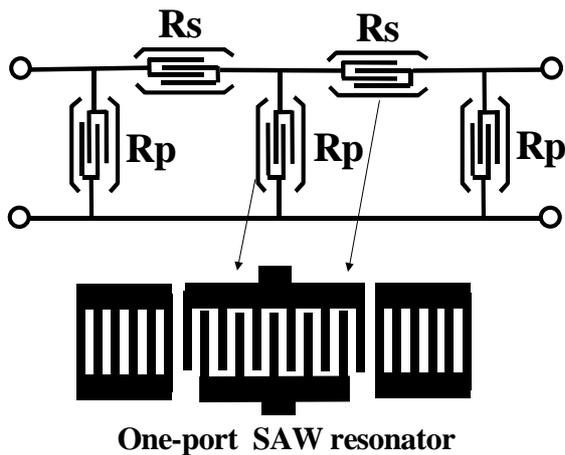
In the early stage of cellular phone popularity until 1992, IIDT type SAW filter is mainly used for RF filters [1]. Fig.1(a) schematically shows an example of the IIDT structure. This structure, however, had the insertion loss limit at 3~4 dB level and required the external matching circuit



(a) IIDT type design



(b) DMS type design



(c) Ladder type SAW filter design

Fig.1 Three kinds of RF SAW filter's design

at that time. To overcome these problems, the ladder type SAW filter and the DMS filter were reported at the same year of 1992 [2][3][4]. Both filter design utilize SAW resonators which are suitable for low-loss characteristics and their designs are resemble to the BAW (Bulk Acoustic Wave) filters with low frequency band such as quartz or ceramics filters.

The filter structures of DMS and ladder type SAW are shown in Fig.1(b) and Fig.1(c) respectively. The DMS filter utilizes two identical resonant modes acoustically coupled in the longitudinal direction. To make bandwidth wide, 1st mode and 3rd mode are selected by symmetrically arranging three IDT as shown in Fig.1(b) on LiNbO₃ substrate[2]. Recently, on 42 degree Y cut-X LiTaO₃ which has the lower TCD (35ppm/°C) than LiNbO₃ (70ppm/°C) as described later in this paper, the DMS filter with wide bandwidth were realized by adjusting film thickness, finger pairs number, and gap between IDTs [5].

Fig.1(c) shows the structure of the ladder type SAW filter. Two types of one-port SAW resonator, the series arm resonator and the parallel arm resonator, which have slightly different resonant frequency each other are electrically coupled through ladder connection in this structure. The impedance of this filter can be matched to 50Ω by adjusting values of static capacitance of these one-port SAW resonators[3]. The fractional bandwidth can be enlarged up to 4% by inserting small inductance (L) into the parallel arm or by enlargement of the resonant frequency differences between two SAW resonators.

The nominal S₂₁ characteristics of these three kinds of RF filters are shown in Fig.2 and Fig.3 comparing them through the ladder type SAW filter's characteristic. The features of these filters are summarized in table.1.

Figures 2,3 and Table 1 suggest the following characteristic features.

- (1)The insertion loss of the ladder type and the DMS are lower than the IIDT. Especially, the

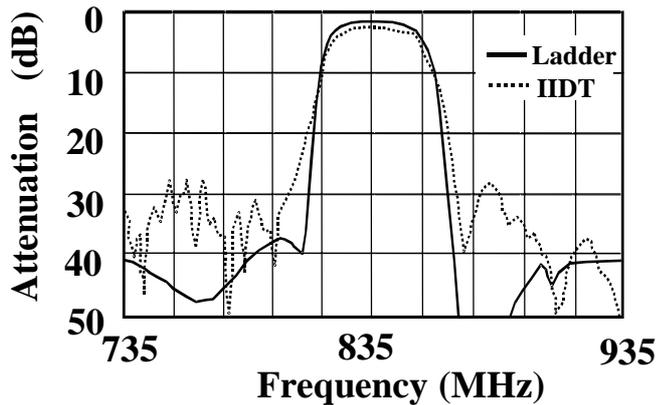


Fig.2 A comparison between ladder and IIDT

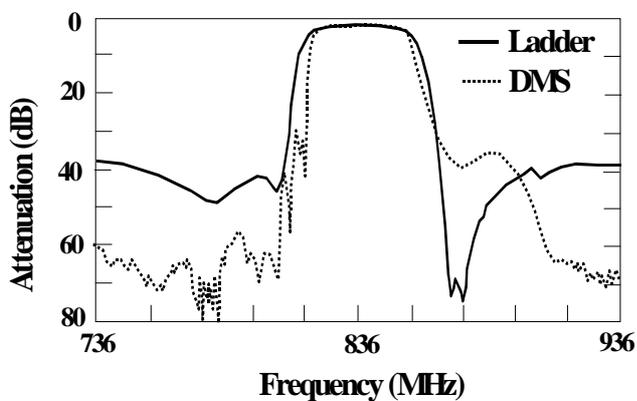


Fig.3 A comparison between ladder and DMS

insertion loss less than 1dB is obtained by the ladder type sacrificing the rejection band attenuation [6].

- (2) The attenuation level of the out-of-band is superior in order of the DMS, the IIDT and the ladder type. However, the DMS has the weak attenuation level at the higher band edge as shown by the hatched area in Fig.3.
- (3) The bandwidth of the ladder type is much wider than that of the DMS as shown in Fig3 and Table 1.
- (4) High power durability of the ladder type and the IIDT are much better than the DMS because the number of finger pairs in the DMS design is smaller than that of the others. In addition, the intercept point(IP3) of the ladder type is the best among these. Then the ladder type is the most suitable for the high

power application.

- (5) The balanced type design is impossible for the ladder type. For that application, we should change it to the lattice type design.

Summarizing these, the ladder type is suitable for the requirement with a low insertion loss, a wide band, and/or a high-power durability, while the DMS is available for a low insertion loss and a high attenuation level of the out-of-band in the low power application. Recently, the IIDT is less used in the RF application for its high insertion loss.

Table 1 The features of RF SAW filters

	Loss	Att.	Band Width	Power Dura.	IP3	Balanced Type
IIDT	3~4dB	25~50dB	variable	good	~37dBm	possible
DMS	2~3dB	25~60dB	~3.5%	bad	bad	possible
Ladder	1~3dB	20~40dB	~4%	good	61dBm	impossible

These RF filters are mounted in the small SMT package shown in Fig.4. The smallest size in this figure is 2.5×2.0×1.0mm while the smallest size in the world announced is 2.0×2.0×1.0mm.

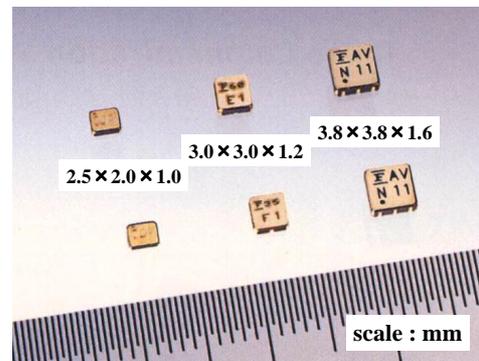


Fig.4 The SMT packages of RF SAW filters

PIEZOELECTRIC SUBSTRATE

The piezoelectric substrates for RF SAW filters of cellular phones are selected by considering the following properties.

- (1) It is better that the substrate has high SAW

velocity, because IDT patterning resolution becomes relaxed as the velocity becomes high.

- (2) TCD (Temperature Coefficients of Delay) must be small in order to minimize the frequency shift of filters by ambient temperature.
- (3) The substrate has the sufficient large value of the electromechanical coupling coefficient k^2 in order to meet the wide band requirement.

From the viewpoint of above items, two kind of piezoelectric substrates listed in Table 2 are widely used for the RF SAW filters. One is 36°Ycut-X LiTaO₃ [10], and the other is 64°Ycut-X LiNbO₃ [11]. Both of them utilize the leaky type SAW (LSAW) with high velocity. LiTaO₃ has the smaller TCD but the medium k^2 , while LiNbO₃ has the large k^2 but the large TCD as shown in Table 2. However, recently, LiTaO₃ is going to be mainly used because LiTaO₃ has the smaller TCD and its drawback of the smaller k^2 is going to be recovered by IDT designing for wide band.

Table 2 Features of piezoelectric substrates

substrate	36°Ycut-XLiTaQ	64°Ycut-XLiNbQ
Velocity	4210 m/s	4742 m/s
TCD	32ppm/°C	79ppm/°C
k^2	5 %	11 %

The recent new design of IDT such as the ladder type and the DMS require the thick thickness of electrode for wide band and low-loss characteristics.

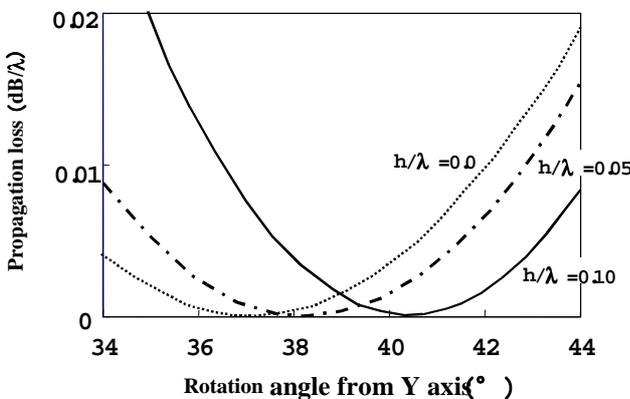


Fig.5 The propagation loss dependency on the rotation angle from Y axis in LiTaO₃

Hashimoto et al.[6] has proposed the idea that 36 degree was not already the optimum cut angle for LiTaO₃ crystal in the case of the increased electrode thickness. They have investigated the rotation angle vs. propagation loss of LSAW by simulation. Fig.5 shows the results. As increasing the film thickness (h/λ), the optimum rotation angle shown by minimum point of propagation loss in Fig.5 becomes larger. The actual filter characteristics using the ladder type design with the film thickness of 0.12

were experimentally measured by varying the rotation angle[6]. From the result shown in Fig.6, the optimum rotation angle is experimentally confirmed to be 42 degree. In Fig.6, the shape factor is defined as the bandwidth of 20dB down divided by that of 5 dB down in the pass-band.

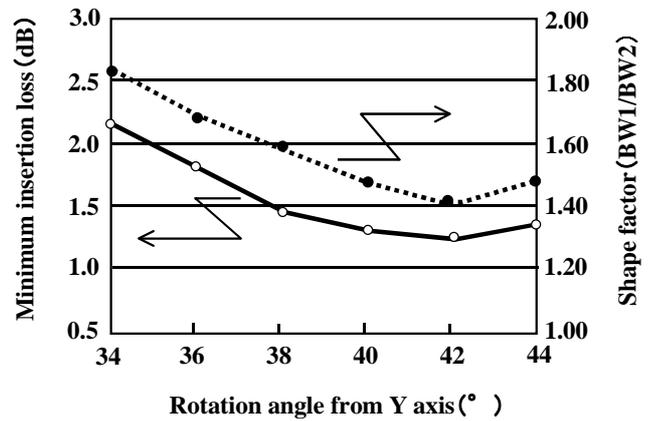


Fig.6 Experimental results for optimizing the cut angle

FABRICATION PROCESS FOR GHz SAW FILTERS

The one of the most important technologies for realization of high frequency SAW filters is fabrication process for fine pattern with sub-micron rule. Fig.7 shows the pattern width of IDT (W) vs. the center frequency of SAW filters (f_0), which relation is decided by the next well-known simple formula.

$$W = V_{idt} / 4f_0 \quad (1)$$

Here, V_{idt} means SAW velocity under IDTs. In this figure, the values of 4000m/s for LiTaO₃, 5000m/s for AT-cut X_lpropagation quartz, and 10000m/s for piezoelectric thin film on diamond film are used as V_{idt} .

The AT-cut quartz and the piezoelectric thin film on diamond film each has the high velocity but they can not be used for RF filters of cellular phones because they doesn't have enough value of k^2 . In the case of using LiTaO_3 , the pattern width of 2.5 GHz filter becomes down to $0.4 \mu\text{m}$. Recent high resolution photolithography techniques in semiconductors make GHz SAW filters possible. If we use an i-line stepper, which uses a 365nm light source, we can realize filters of up to 2.5GHz. When using an excimer stepper having a resolution of $0.13\text{--}0.18 \mu\text{m}$, filters in the range of 5.5–7.7 GHz can be produced. The specification and market size of the demanded GHz filter, through put,

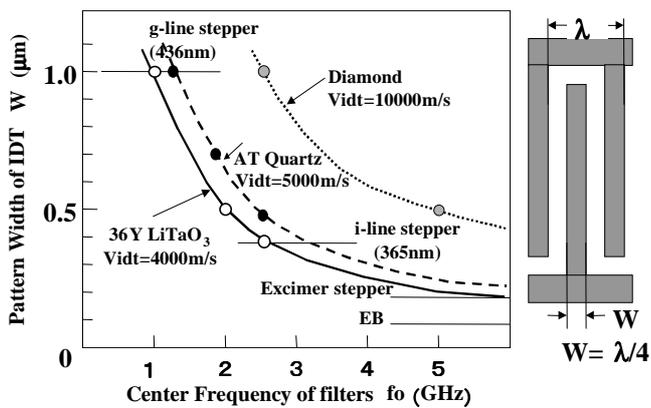


Fig.7 The frequency of filter vs. pattern width

yield, and the price of equipment must be considered in deciding which apparatus is suitable. From this viewpoint, the i-line stepper is suitable for mass-production of 1.5 GHz–2.5 GHz SAW filters.

The etching method is another key technique in the fabrication of GHz filters. The dry etching methods, especially the reactive ion etching (RIE), is very suitable for SAW devices to replace the conventional wet etching methods. As the damage on the piezoelectric substrate by RIE is well suppressed compared with other dry etching method such as ion-milling, no deterioration in filter characteristics and good reliability are observed. Using BCl_3 gas, we can cleanly etch Al or slightly doped Al film without corrosion or residuum. This RIE method has already been put into practical use.

Combining these two techniques, exposure by i-line stepper and RIE, we fabricated an $0.4\mu\text{m}$ -rule pattern and produced 2.5GHz filters. Fig.8 shows a SEM photograph of an $0.4\mu\text{m}$ -rule IDT made by the two techniques, and shows the S_{21} characteristic of a 2.45

GHz filter designed by the ladder type structure for wireless LAN. This filter has a 100 MHz band-width with a 4dB maximum insertion-loss, an out-of-band rejection higher than 30 dB and a high shape factor as shown in Fig.8.

Further high frequency filters have been investigated by Yamanouch et. al. using EB exposure[7]. We also

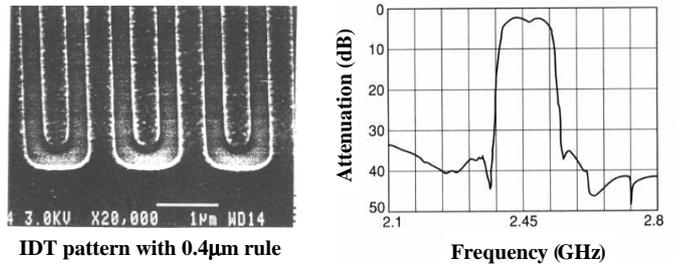


Fig.8 IDT pattern and 2.4GHz SAW filter

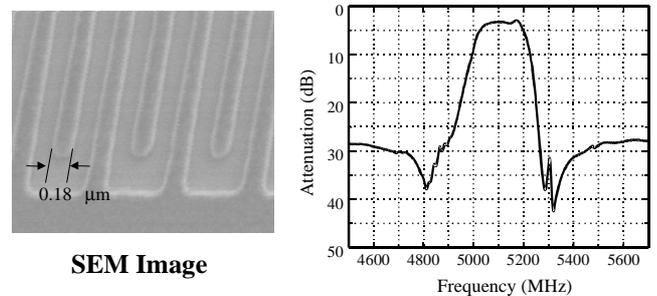


Fig.9 IDT pattern and 5 GHz SAW filter

tried to make 5GHz filters by EB exposure considering using excimer stepper in mass production. Except for the exposure process, almost the same process as 2.5GHz filters was used in the experiment. Unlike the ultraviolet optical exposure, the EB exposure has the inherent problem such as back scattering of electron from LiTaO_3 substrate with heavy density. We improved this problem by selecting the resist type and optimizing EB exposure pattern. Fig.9 shows Al-IDT pattern delineated by EB exposure and RIE. The line and space with 0.18 micron rule was cleanly fabricated. The obtained characteristic by the ladder design showed 5.1 GHz center frequency, 4dB insertion loss with 150MHz bandwidth, 3 dB minimum insertion loss and more than 25 dB stop band rejection as indicated in Fig.9. This filter characteristic is available for 5GHz band Wireless Local Loop applications. In the near future, the 4th generation cellular system is said to use the frequency

band higher than 3 GHz. It is confirmed from this experiment that the ladder type SAW filter is also useful for the 4th generation applications.

DEVELOPMENT ON HIGH POWER DURABILITY AND AN ANTENNA DUPLEXER

Fig. 10 shows the block diagram of RF circuit in the cellular phone. Many SAW filters are used in the RF circuit. In the front-end circuit, there is an antenna duplexer to which the high RF power of around 1W is applied. The improvement on power durability of SAW filters is very important for realization of SAW antenna duplexer.

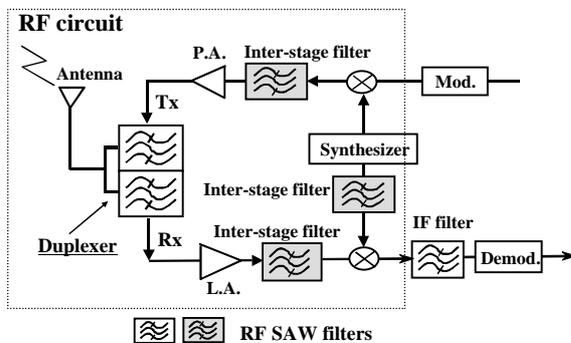


Fig.10 The block diagram of RF circuit

So far, much effort has been spent on improving the power durability by finding new materials to replace the current material Al. The slightly metal doped Al films, such as Cu, Ti, and Si, have been investigated[8]. The single crystal film of Al and the highly textured Al film oriented [111] direction were also tested in the past[9]. However, those materials had insufficient power durability for 1W.

We have proposed the three layered film for high power durability. Fig.11 shows this concept. In this film structure, the different metal is inserted among the Al-Cu film. If the middle layer metal is mechanically strong, the punch through of void and the migration of Al are thought to be prevented by the middle layer. We tested many metals as a middle layer and have found that Cu was the best. Fig.12 shows the lifetime vs. the input RF power. The lifetime is drastically improved compared with the current material of Al-Cu single

layered film. The sufficient lifetime of 500 thousand

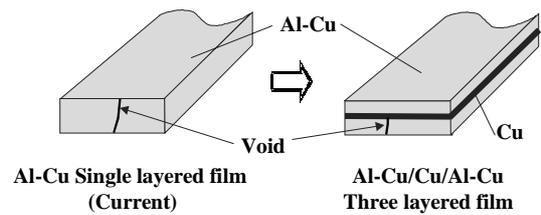


Fig.11 The structure of three layered film.

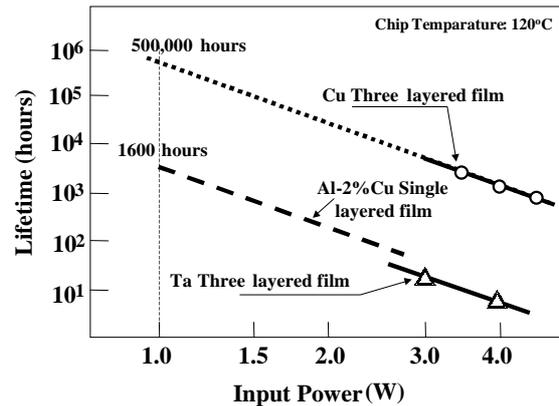


Fig.12 The lifetime vs. input power.

hours is obtained at 1W power level. The reason why Cu is the best is that the middle layer Cu changes to CuAl_2 without high temperature annealing which is very hard for mechanical stress.

Using this high power tolerable film and the ladder type filter design, we have developed SAW duplexer with the smaller size than that of dielectric one. In addition to these technologies, we have also developed the key technology about duplexer package. The features of technologies are summarized as follows.

- (1) The ladder filter of the lower frequency side is designed so as to put the series arm resonator at the antenna port side, while the parallel arm resonator is arranged at the antenna side for the higher frequency side filter (see Fig.13). Thanks to this configuration, the impedance matching circuit of the lower frequency filter side is omitted, and that of the higher frequency filter side is the short phase rotation element like strip line. This contributes to the low-loss and the small size of the antenna duplexer
- (2) The strip line for phase rotation is folded on the back side of the package like Fig.14. And the strip line made of Tungsten is plated by gold in order to reduce

the resistance. This also contributes to the low-loss and miniaturization of the package.

As the result, the comparable characteristics to the dielectric duplexer are obtained with an advantage of volume reduction that is about 1/8 of the dielectric duplexer. Fig.14 shows the photograph of SAW duplexer and Fig.15 shows its S_{21} characteristics for AMPS specification. The typical frequency response are

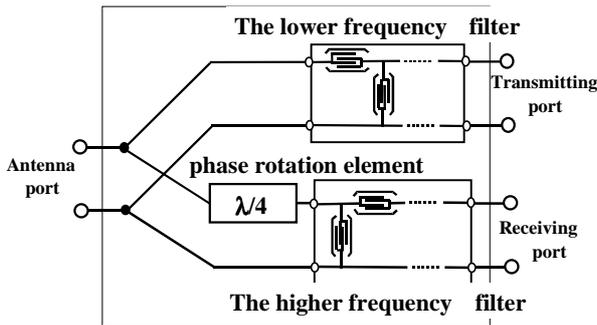


Fig.13 The structure of antenna duplexer

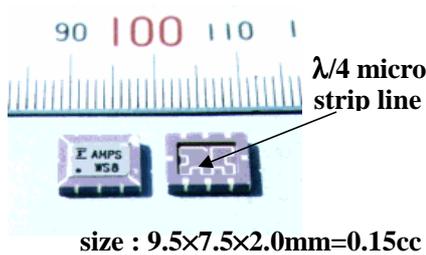


Fig.14 The photograph of SAW duplexer

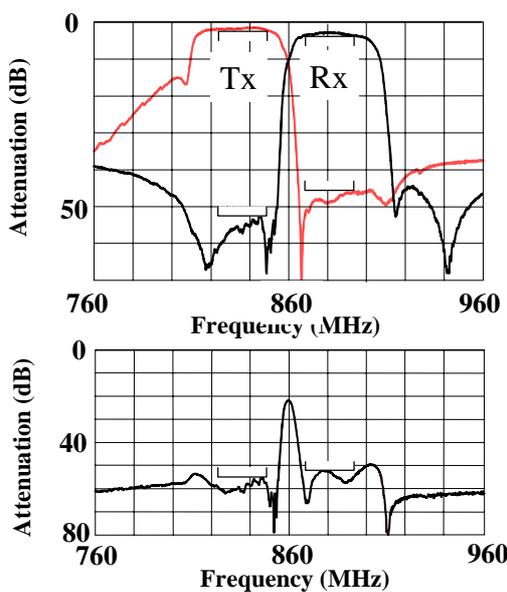


Fig.15 S_{21} characteristics for AMPS duplexer

2.0/3.6dB(Tx/Rx) insertion loss, 53/45dB stop band attenuation, and 55/52dB Tx-Rx through isolation.

Further miniaturization of an antenna duplexer has been also progressed. Recently, we developed 5mm square duplexers shown in Fig.16. The main points of improvement for the former developed duplexer are as follows.

- (1) Two SAW filters are fabricated on one chip.
- (2) LTCC (Low Temperature Co fired Ceramic) package is used to replace W by Cu for reducing the resistivity of conductors.
- (3) The phase rotation line is inserted again into the middle of the layered ceramics.

By using these technologies, the size of AMPS duplexer is reduced to be 5x5x1.5 mm which is a quarter of the current duplexer as shown in Fig.16. The characteristics are almost the same as Fig.15.

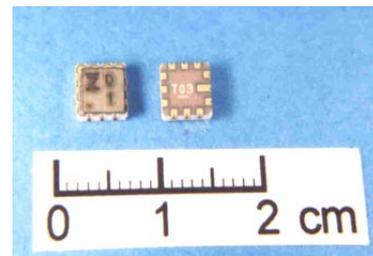


Fig.16 A five mm square SAW duplexer.

FUTURE TREND OF RF SAW FILTER DEVELOPMENT

In the future, the frequency of mobile communication is going up to the higher frequency. For example, WLL and ITS system are planned to use 5 GHz band. And 4th generation system is also planned to use the frequency higher than 3GHz. On the other hand, high power durability must be progressed for 2GHz band filters to realize antenna duplexer of IMT2000 (the 3rd generation). Fig.17 shows the future trend of development in the viewpoint of the power durability and the center frequency. The frontier line of RF SAW development is laid at this area.

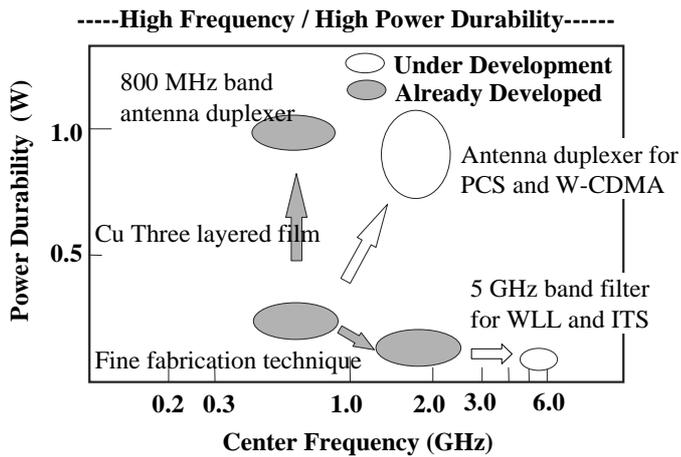


Fig.17 Trend of RF SAW filter development

CONCLUSIONS

The present and future of the development on RF SAW filters are described. The low-loss and the small sized SAW filters from 800 MHz to 5 GHz band are already realized. Recently, the further miniaturized antenna duplexer of 800 MHz band is also realized. In the near future, the further improvement on the higher frequency filter than 3GHz and antenna duplexers of 2GHz band will be the important subject for RF SAW filters.

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