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Research progress in SAW filter banks

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Abstract: SAW (Surface Acoustic Wave) filter bank is a single input, single or multi-output device consisting of multi-SAW-filters with input interconnection network or switch circuits, and can be divided into two categories: channelizer (multi-output) and switchable (programmable, single output). The former is mainly used in military channelized receiver for spectrum analysis; the latter has wide application in frequency synthesizer and frequency-hopping radar and communication system receiver as anti-jamming filter, and has been widely used in various military electronic equipments ever since the 1970s. Research abroad was done mainly by Americans, few documents on related work done by Japan and Russia are available. Domestic research started in the 1980s, mainly by No. 26 Research Institute, China Electronics Technology Group Co., Institute of Acoustics, Chinese Academy of Sciences, No. 23 and No. 25 Research Institute, China Spaceflight Tech. Group Co. This paper first briefly introduces Chinese and foreign research on SAW filter banks; then discusses research progress in device design, the input interconnection network or switch circuit and miniaturization; and ends in a brief perspective of developing trends in future.

Key words: SAW, Channelizer, Switchable, Filter banks, Progress
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INTRODUCTION

SAW (Surface Acoustic Wave) filter bank is a single input, single or multi-output device consisting of multi-SAW-filters, input interconnection network or switch circuits, and can be divided into two categories: channelizer (multi-output) and switchable (programmable, single output). The former is mainly used in military channelized receiver for spectrum analysis; the latter has wide application in frequency synthesizer and frequency-hopping radar and communication system receiver as anti-jamming filter, and has been widely used in various military electronic equipments ever since the 1970s. Abroad research was done mainly by Americans, few documents on work done by Japan and Russia are available (Webb and Banks, 1976; Slobodnik *et al*., 1979a; 1979b; 1981; Collines and Grant, 1981; Allen *et al*., 1979; Solie and Wohlers, 1981; Solie *et al*., 1988; Jen and Harmann, 1993; Gopani *et al*., 1994; Misu *et al*., 1988; Doberstein *et al*., 2000). Domestic research started in the 1980s, mainly by No. 26 Research Institute, China Electronics Technology Group Co., Institute of Acoustics, Chinese Academy of Sciences, No. 23 and No. 25 Research Institute, China Spaceflight Tech. Group Co. (Huang *et al*., 1993; 2001; Li *et al*., 1996; Ou *et al*., 1996; He *et al*., 1998; 2002; 2003; 2004; He and Wang, 1997). Table 1 lists main research results. To realize channellization, besides multi-filters and input interconnection network design, there are many other design options like multi-coupler, acoustic reflecting grating, tapered transducer, acoustic Bragg lens, etc. However, a series of individually designed filters suitably combined with input interconnection network yield better performance. Compared to the domestic researchers, foreign researchers deal with fewer channel number but have better stopband suppression and triple-transit suppression. Part II and Part III below discuss progress in research on device design, interconnection network or switch circuit and miniaturization, Part IV discusses future develop trends.

Table 1 Comparison of typical parameter for SAW filter bank

Cent freq (MHz)	Chan num	Chan BW (MHz)	Chan INTERV (MHz)	IL (dB)	Stopband rejection (dB)	Substrate material	Temp coeff (10^{-6}/°C)	R & D group	Ref.
SAW channelizer filter bank									
200	10	5	5	35		YX quartz	24	Naval Research Laboratory (USA)	Webb and Banks, 1976
325	16	10	10	19.5^*	>50	MDC-LiTaO$_3$	64	Rome Air Development Center (USA)	Slobodnik *et al.*, 1979b
325	16	20	10	22.3^*	>50	MDC-LiTaO$_3$	64		Slobodnik *et al.*, 1979b
320	8	20.3	20	33.5±1.5	38	MDC-LiTaO$_3$	64		Slobodnik *et al.*, 1981
266	8	9	<9	36±1.5	40	LiNbO$_3$	≥75	Hughes Aircraft Company (USA)	Collines and Grant, 1981
350	9	31.25			40~50	LiNbO$_3$	≥75	Texas Inc. (USA)	Collines and Grant, 1981
625	9	31.25	31.25	15		YZ-LiNbO$_3$	94	Motorola Inc. (USA)	Allen *et al.*, 1979
85	16	1	0.5	16	<30	YZ-LiNbO$_3$	94	Sperry Research Center (USA)	Solie and Wohlers, 1981
180	14		8.6	19	40	YZ-LiNbO$_3$	94	Unisys Corporation (USA)	Solie *et al.*, 1988
277.5	7	20.5	20	13.5^*	60	YZ-LiNbO$_3$	94	Sawtek Inc. (USA)	Jen and Hartmann, 1993
350	5×2	20	20	18	50	Y128° LiNbO$_3$	75	Hartmann Research Inc. (USA)	Gopani *et al.*, 1994
155	10		10	19±1.7	>40	Y128° LiNbO$_3$	75	Mitsubishi Electronic Co.	Misu *et al.*, 1988
310	10	20	20	18±1	>30	YZ-LiNbO$_3$	94	No. 25 Research Institute, China Spaceflight Tech. Group Co.	
200	11	15	10	22±1	>35	YZ-LiNbO$_3$	94	No. 23 Research Institute, China Spaceflight Tech. Group Co.	
200	20	5	5	20±1	>40	Y128° LiNbO$_3$	75	No. 26 Research Institute, China Electronics Technology Group Co.	Huang *et al.*, 1993
350	20	10	10	22±1	>40	Y128° LiNbO$_3$	75		Li *et al.*, 1996
35	5	2.1	2	15	>40	Y128° LiNbO$_3$	75		Ou *et al.*, 1996
275	15	10	10	20±1.5	>40	Y112° LiTaO$_3$	18	Institute of Acoustics, Chinese Academy of Sciences	He *et al.*, 1998
425	15	10	10	20±1.5	>35	Y112° LiTaO$_3$	18		He *et al.*, 1998
350	21	7.5/15/10	6.25/10/7.5	19±0.5	>40	Y128° LiNbO$_3$	75		He *et al.*, 2004
Switchable SAW filter banks									
313	9	3	3	20	60	ST quartz	0	Rome Air Development Center (USA)	Slobodnik *et al.*, 1979a
414	9	3	12	26	60	ST quartz	0		Slobodnik *et al.*, 1979a
125	24	>8.3	>8.3	3^*	>40	Y64° LiNbO$_3$	70	ONIIP, Russia	Doberstein *et al.*, 2000
375	16	27	3.2	20.6	>40	Y128° LiNbO$_3$	75	No. 26 Research Institute, China Electronics Technology Group Co.	Huang *et al.*, 2001
152.5	8	13	13	16±0.5	>40	Y112° LiTaO$_3$	18	Institute of Acoustics, Chinese Academy of Sciences	
VHF	16	0.4		13±0.5	>70	ST quartz	18		He *et al.*, 2002
45	8	>1.3	>1.3	3	50	Y64° LiNbO$_3$	70		He *et al.*, 2003
275/375	32	21	3	14±1	>35	Y128° LiNbO$_3$	75		He *et al.*, 2003

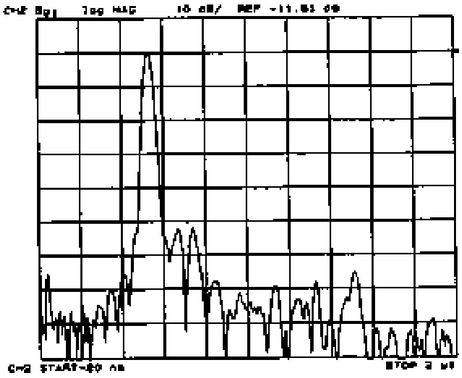
FILTER DESIGN PROGRESS

The SAW filter's small size, light weight and steep transition band, led to their role change from paper design to actual use, in military equipment such as channelized receiver. One disadvantage is high insertion loss, due to bidirectional loss: input (emitting) interdigital transducers (IDT) emit acoustic wave to both directions, only those heading for output IDT are received, so that only half of the energy is utilized, which results in 3 dB loss; while output (receiving) IDT has the same 3 dB loss, thus resulting in 6 dB total bidirectional loss. Take passband ripples induced by triple-transit signal, actual filters have insertion loss of up to 15 dB or more. Early SAW filter bank design adopted bidirectional transducers resulting in high insertion loss. The system designer must use high gain amplifier to compensate for insertion loss, this will lead to system power consumption. So reducing SAW filter insertion loss has been the researcher's goal since the 1960s. This goal is becoming more urgent because mobile communication needs and attracts more manpower and material resources. A breakthrough was made in the late 1980s and early 1990s when minimum insertion loss could be less than 1 dB in mobile. Low insertion loss filter is used in the design of SAW filter bank.

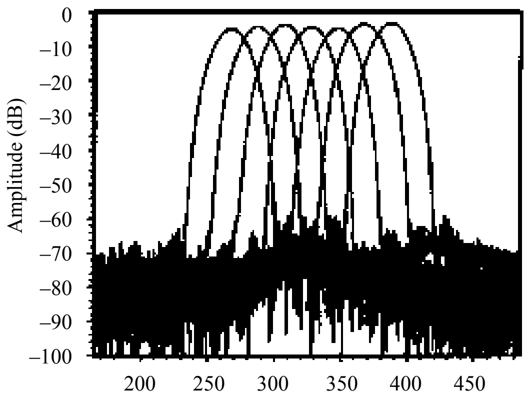
Frequently used low insertion loss structure includes: Single Phase Unidirectional Transducer (SPUDT), longitudinally-coupled double mode SAW (DMS) filter, transversally-coupled resonantor filter, ladder-type resonantor filter. SPUDT keeps the characteristics of transversal filter, like linear phase and flexible bandwidth design in certain range, all these contribute to SPUDT's wide application. For channelizer filter bank, as each channel needs the same bandwidth, we can only use SPUDT structure, whose drawback is the relatively higher insertion loss of at least 3 dB. For other structures, insertion loss is less, they do not have the transversal filter's characteristics, lack a linear phase, and have poor flexibility in bandwidth design or with too narrow bandwidth (transversally-coupled resonantor filter), have poor near stopband suppression (DMS filter), poor far stopband suppression (ladder-type resonator filter), all of which restrict their applications. We could only find DMS filter used in frequency-hopping communication system as switchable filter bank application.

In 1993, Hartmann Research Inc. USA reported the experimental result of a 5-channel SAW filter bank (Jen and Hartmann, 1993). Y128°-$LiNbO_3$ substrate and SPUDT structure were used in their filter design whose parameters were bandwidth of about 7%, insertion loss of around 17 dB, stopband rejection and triple-transit suppression of more than 60 dB.

Fig.1 is the experimental result of 7-channel filter bank reported by SAWTEK Inc. USA in 1994 (Gopani *et al.*, 1994). YZ-$LiNbO_3$ substrate and SPUDT structure were adopted in the filter design with bandwidth about 7%, individual filter insertion loss of about 13.5 dB (Fig.1b), stopband rejection of more than 63 dB, triple-transit suppression (Fig.1a) of more than 65 dB. If bidirectional transducers are used and the triple-transit suppression of the SAW filter is hoped for 65 dB, its insertion loss will be more than 25 dB.



(a)



(b)

Fig.1 Experiment results of 7-channel filter bank developed by SAWTEK Inc., USA
(a) Time domain response of individual filter; (b) Frequency response of filter banks

Fig.2 is the experiment result of 5-channel filter bank given by No. 26 Research Institute, China Electronics Technology Group Co. in 1996 (Ou *et al.*, 1996). Y128°-LiNbO$_3$ substrate and SPUDT structure used had filter bandwidth of about 7%, filter bank insertion loss of about 15 dB, stopband rejection of more than 40 dB, shape factor of less than 1.6.

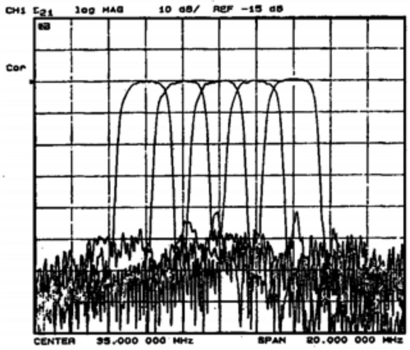


Fig.2 Experimental results of 5-channel filter bank developed by No. 26 Inst.

The Institute of Acoustics, Chinese Academy of Sciences adopted separately SPUDT, the slanted fingers SPUDT and DMS filter structure in developing the 21-channel SAW channelized filter bank and 8-channel, 16-channel, 32-channel switchable SAW filters (He *et al.*, 2002; 2003; 2004). Twenty-one-channel SAW channelized filter bank's individual filter uses Y128°-LiNbO$_3$ substrate and SPUDT structure with bandwidth of about 6%, insertion loss of about 9~12 dB, stopband rejection of more than 40 dB, shape factor of less than 1.6. The 8-channel switchable filter bank's individual filter design adopts Y64°-LiNbO$_3$ substrate and DMS filter structure with bandwidth of about 3%, insertion loss of less than 2 dB, stopband rejection of more than 50 dB. The 16-channel SAW switchable filter bank's individual filter uses ST-cut quartz substrate and SPUDT structure with bandwidth of about 0.3%, insertion loss of about 5 dB, stopband rejection of more than 35 dB. The 32-channel SAW switchable filter bank's individual filter uses Y128°-LiNbO$_3$ substrate and the slanted fingers SPUDT structure with bandwidth of about 5%~8%, loss of about 8~9 dB, stopband rejection of more than 40 dB. The experimental results and frequency response of the filter bank mentioned above will be given in Part III.

PROGRESS OF RESEARCH ON THE INTERCONNECTUION NETWORK OR SWITCH CIRCUIT AND MINIATURIZATION

The interconnection can be performed (1) by using power splitters, (2) by implementing a constant-*k*/M derived ladder network, (3) by feeding the IDT into a series/parallel network, each method has its own advantages, drawbacks and scope of application.

Good isolation between channels resulting in small mutual interference can be obtained by using power splitters. However, power splitters introduce loss which increases with the number of channels, have big size, and are only suited for filter bank networks with few channels. The above-mentioned 7-channel SAW channelized filter bank (Part II) employs this as interconnection network with loss of more than 8 dB.

The constant-*k* ladder network is shown in Fig.3 (Webb and Banks, 1976); low-pass network is composed of SAW filter input transducer as parallel arm and inductance as series arm. If the mirror impedance of each segment is set to 50 Ω, small input VSWR can be achieved. As 50 Ω resistance load is connected in the terminal, the loss is more than that series/parallel network and is about 7 dB for 10-channel network.

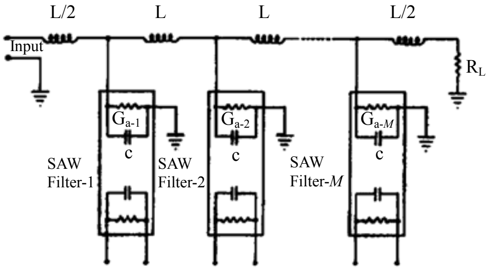


Fig.3 Constant-*k* ladder SAW filter bank

Fig.4 is the experimental result of the 20-channel SAW channelized filter bank developed by No. 26 Institute in 1996 (Li *et al.*, 1996). Channel bandwidth and interval are 10 MHz each. The filter design employs bidirectional transducers and Y128°-LiNbO$_3$ substrate. The input interconnection was implemented by using a constant-*k* ladder network which was shown to have insertion loss of about 22 dB, stopband rejection of over 45 dB and shape factor of less than 2.

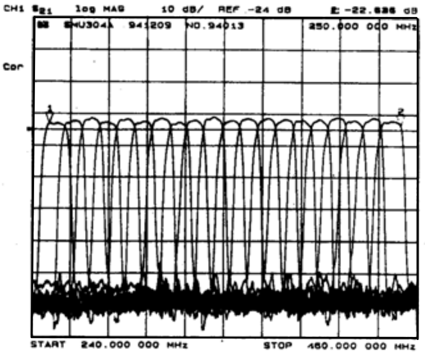


Fig.4 Frequency response of 20-channel SAW channelizer filter bank developed by No. 26 Institute

An M derived ladder network evolved from a constant-*k* ladder network: replaced series inductance with one inductance and one capacitance parallel network in a constant-*k* ladder network. This was done to increase harmonics suppression. A 10-channel filter bank with insertion loss of about (19±1.7) dB was developed by Mitsubishi Electronic Co., Japan in 1988 (Misu *et al*., 1988) using M derived ladder network. Third harmonics suppression was effectively improved to 42~52 dB, while best harmonics suppression was only 28 dB using a constant-*k* ladder network.

Series/parallel network is shown in Fig.5 (Slobodnik *et al*., 1979a; 1979b), due to no resistance components, low network loss can be achieved. Disadvantage is poor isolation between channels, resulting in high mutual interference, which makes the debugging difficult. A 9-channel filter bank with channel bandwidth of about 0.3%, total bandwidth of about 7%, insertion loss of about 20 dB (network loss 6 dB), stopband rejection of more than 63 dB and using series/parallel network, was developed by Rome Air Development Center USA in 1979 (Slobodnik *et al*., 1979a; 1979b).

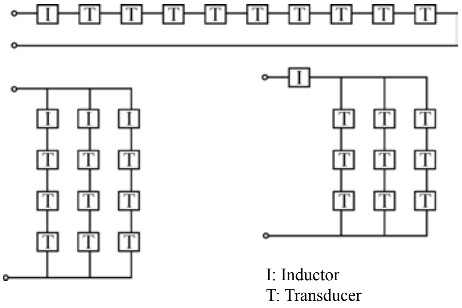
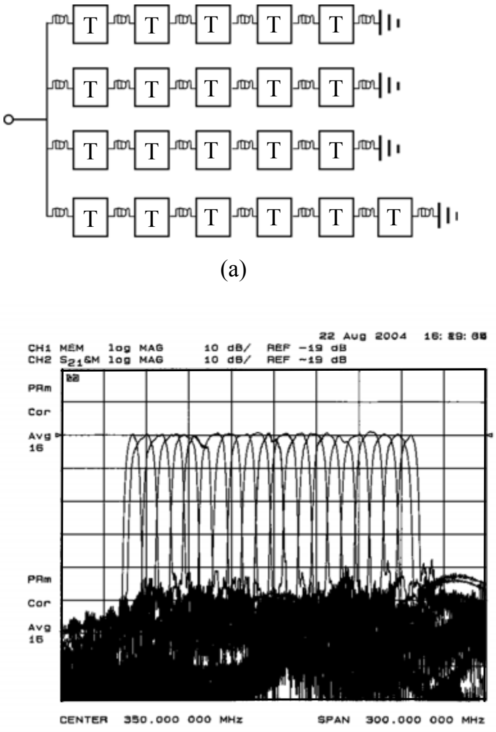


Fig.5 Illustrations of three of the input transducer interconnection schemes

The author improved the above series/parallel network by adding tuning element (inductance or capacitance) to both ends of each transducer, which decreases network loss. A 15-channel filter bank with Y112°-$LiTaO_3$ as substrate resulted in bandwidth channel interval of 10 MHz, total bandwidth of 150 MHz (55%), insertion loss of about 20 dB (network loss of 5 dB) (He *et al*., 1998). Twenty-one-channel filter bank with Y128°-$LiNbO_3$ substrate and SPUDT structure resulted in channel bandwidth of 15 MHz, insertion loss of 19 dB (network loss 7 dB), refer to Fig.6 (He *et al*., 2004).



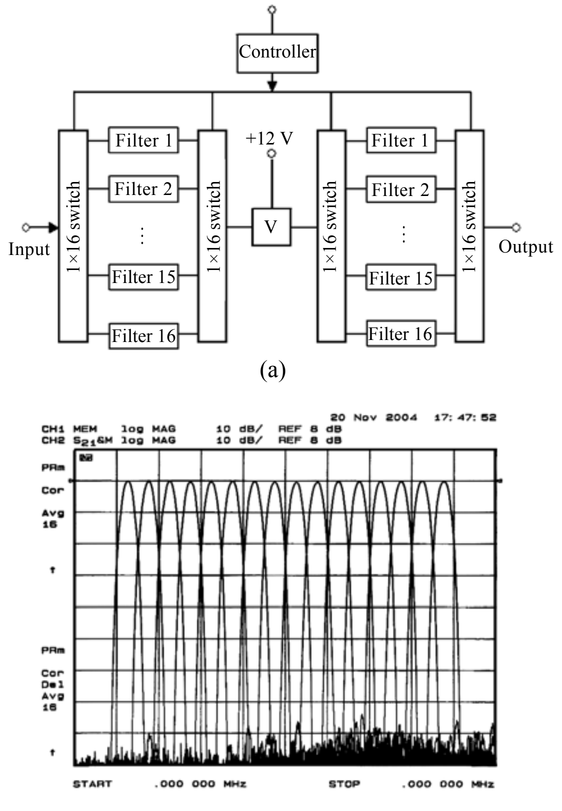
(a)

(b)

Fig.6 Input network (a) and freq. response (b) of 21-channel filter bank by IACAS

For switchable SAW filter bank, earlier researchers used interconnection network as input, switch array as output. Small switch time of about 100 ns is the advantage; drawback is the loss brought by the interconnection network. The above-mentioned 9-channel filter bank developed by Rome Air Development Center USA employed this scheme (Slobodnik *et al*., 1979a; 1979b). The author introduced dual-switch array program in 1997 (He and Wang, 1997), namely input interconnection network is replaced by switch array: this can reduce insertion loss and nonuniformity of insertion loss from interconnection network. The drawback is longer switch time of about μs, because time delay of the filter is included. μs switch time can satisfy most systems, for the extreme requirements case on switch time, input interconnection network and output switch array can be used. The Institute of Acoustics, Chinese Academy of Sciences (IACAS) developed 16, 8, 32 channel switchable filter bank with dual-switch array scheme.

Fig.7 is a block diagram (Fig.7a), frequency response (Fig.7b) of 16-channel switchable filter bank: gain 7.5~8 dB (taking out amplifier gain of 20.5 dB, a two-stage filter bank has about 13 dB insertion loss (including switch)), stopband rejection of more than 73 dB (He *et al.*, 2002). Fig.8 is frequency response of 8-channel SAW switchable filter bank with insertion loss of less than 3 dB, stopband rejection of more than 50 dB (He *et al.*, 2003).



(a)

(b)

Fig.7 Block diagram (a) and frequency response (b) of 16-channel switchable filter bank by IACAS

Fig.9 is the frequency response of a 32-channel SAW filter bank with insertion loss of less than 15 dB, 9 dB less than conventional one (24 dB); volume of less than 150 cm^3, volume 1/3 that of conventional one (450 cm^3) (He *et al.*, 2003).

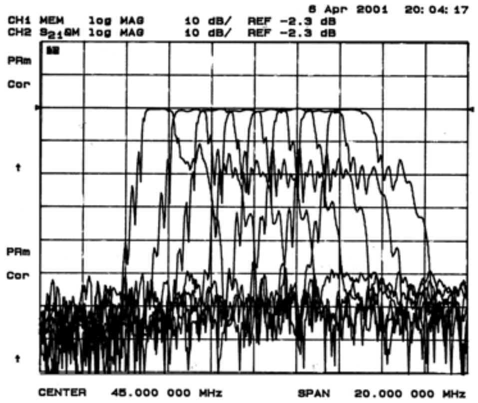


Fig.8 The frequency response of 8 channel switchable SAW filter bank by IACAS

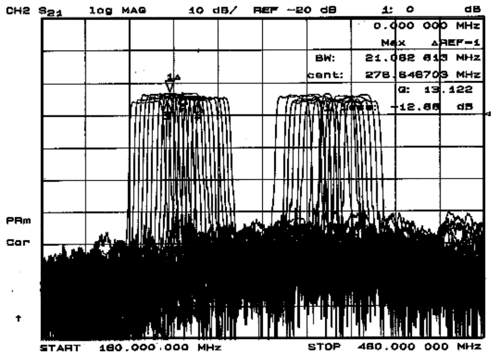


Fig.9 Magnitude frequency response of 32 channels swithchable SAW filter bank by IACAS

TRENDS IN FUTURE

From authors' viewpoint, there are several trends in the future:

(1) Higher frequency; (2) Wider bandwidth; increased channel bandwidth or channel number; (3) Reduced loss: includes device and network loss; (4) Improved performance of device: includes passband ripple, group delay variation, phase characteristics, stopband rejection and triple-transit suppression; (5) Improved temperature characteristics; (6) Miniaturization. These mentioned above are for the following

applications: military electronic equipment needs higher operating frequencies, wider bandwidths, better performance. All these contribute to higher requirements of devices. Certain requirements are inter-related, namely improved temperature characteristics help to increase channelized receiver's frequency detection precision, and improve anti-jamming ability of communication system. Technically speaking, temperature stability could be improved only via using high temperature-stable substrate material. While temperature-stable material has low electromechanical coupling coefficient, it is only suited for narrow bandwidth, when it is used for wider bandwidth device, insertion loss will increase. Therefore, work should be done in reducing insertion loss. In Part III, it is mentioned that the author used Y112°-$LiTaO_3$ substrate to design 15-channel filter bank, with temperature coefficient being 1/4~1/5 that of using $LiNbO_3$ as substrate. As the modified series/parallel network is adopted to reduce loss, insertion loss is comparable with filter bank with $LiNbO_3$ substrate. One more example, lower insertion loss is obtained by using DMS filter, but the problem of frequency response should be solved to get better shape factor.

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