Microwave SAW Bandpass Filters for Spacecraft Applications

Hideyuki Shinonaga and Yasuhiko Ito

Abstract—**Surface acoustic wave (SAW) bandpass filters are small in size, light in weight, and reliable, and can be designed to possess very sharp frequency selectivity and/or a linear phase response. When such stringent filter characteristics were required, not a few satellites used SAW bandpass filters in their transponders in spite of their relatively large insertion losses. These on-board SAW bandpass filters were limited to be operation in the IF (lower than 400 MHz) frequency range. This paper describes microwave SAW bandpass filters for spacecraft applications. Two SAW bandpass filters were designed and fabricated in the 1.5 GHz band using temperature-stable ST-cut quartz substrates. The SAW bandpass filters were then assembled in a SAW filter bank. One unique feature of the SAW filter bank is that a broader band is available merely by adding the outputs of SAW bandpass filters adjacent in the frequency domain. Measured electrical responses as well as results of a transmission experiment show satisfactory performance. Finally, effects of the temperature and aging stability characteristics are investigated based on the measured and calculated responses.**

I. Introduction

MICROWAVE filters are indispensable to spacecraft in order to select and/or reject frequencies in certain ranges from a spectrum covering a large range of frequencies. Various types of electromagnetic wave filters have been used as microwave filters on-board the spacecraft in accordance with required filter characteristics. These include coaxial resonator filters, cylindrical waveguide cavity filters, rectangular waveguide filters, dielectric resonator loaded cavity filters, and microstrip filters [1]–[4]. When very sharp frequency selectivity is required in order to efficiently utilize a limited frequency spectrum, the required number of cavities or stages will become large. Consequently, these filters will become long and large. For such applications, miniature surface acoustic wave (SAW) filters [5]–[7] and/or magnetostatic wave (MSW) filters [4], [8] may be attractive. At present, SAW technologies are well-matured, whereas MSW technologies need further improvements for practical applications. Hence, SAW filters are treated in the present paper.

SAW filters are classified as elastic wave filters. The velocity of a SAW is approximately 10^{-5} times that of electromagnetic waves. This property makes SAW filters much smaller and lighter than the electromagnetic wave filters, even when a large number of transducer taps are required to realize very sharp frequency selectivity. In addition, SAW filters are fabricated on the surface of a piezoelectric substrate, so that they are generally more rugged and reliable [6]. SAW bandpass filters are transversal filters, so the amplitude and phase responses can be designed independently, which is never feasible with the electromagnetic wave filters based on the theory of *LC* filters [5]–[7]. Furthermore, a linear phase finite-duration impulse response (FIR) digital filter [9] can be implemented with SAW bandpass filters. A distinct drawback of SAW bandpass filters is their relatively large insertion losses. However, this can be solved by the proper design of transponders with acceptable dc power consumption, especially in the design of G/T's and level diagrams. As a consequence, not a few spacecraft used SAW bandpass filters, when very sharp frequency selectivity, a linear phase response, and/or a high rejection level were required. These include the Voyager, Pioneer-Venus satellites, the Tracking and Data Relay Satellite System (TDRSS) [10] and the International Maritime Satellite Organization (INMARSAT) second generation satellite. However, these on-board SAW bandpass filters were limited to be operation in the IF (less than 400 MHz) frequencies.

In this paper, microwave SAW bandpass filters are discussed for spacecraft applications. Design and fabrication of *L*-band SAW bandpass filters are described in Section II. Measured electrical responses of a SAW filter bank and results of a transmission experiment are also presented in Section II. Section III discusses the temperature and aging stability characteristics of the microwave SAW filter bank based on the measured and calculated responses. Finally, conclusions are provided in Section IV.

II. *L*-Band SAW Bandpass Filters

Two SAW bandpass filters were designed and fabricated in the 1.5 GHz band. The amplitude and phase frequency responses of these SAW bandpass filters were so designed that a coherent sum of the amplitude and phase of filters adjacent in the frequency domain provides a broadband channel whose bandwidth is a sum of the passbands of these filters and the transition bandwidths lying between them [11], [12]. This bandwidth-variable feature is suited for a multiplexer with contiguous channels [1], whose bandwidths can be changed on demand. An ex-

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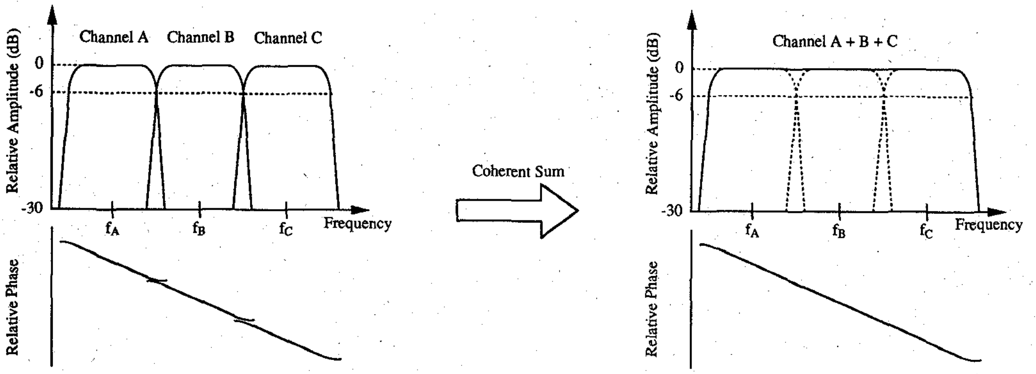


Fig. 1. Amplitude and phase frequency responses of three SAW bandpass filters and those of a combined channel.

TABLE I
MAJOR PARAMETERS OF FABRICATED SAW BANDPASS FILTERS

Piezoelectric Substrate	ST-Cut Quartz
Transducer Material	Aluminum
Type of Input and Output Transducers	Withdrawal Weighted Group-Type Transducer
Number of Transducer Electrodes	Input Transducer: 1300 Output Transducer: 1500
Width of Transducer Electrode	0.51 μm
Transducer Thickness	400 Å
Aperture	25.5 μm
Chip Size	2.5 × 6.0 × 0.37 mm^3
Package Size	7.5 × 12.5 × 3.8 mm^3
Typical Insertion Loss	40 dB

ample of the amplitude and phase responses of three SAW bandpass filters centered at f_A, f_B and f_C is shown in Fig. 1 together with a coherently combined response. The amplitude responses cross over at the -6 dB points and reach -30 dB before entering the passbands of other channels. The phase responses are continuous from channel to channel, so the design of a linear phase FIR filter [9] was applied to these SAW bandpass filters. As a piezoelectric substrate, ST-cut quartz was selected in due consideration of its superior temperature stability and the narrow fractional bandwidth of approximately 0.4% required. The heritage of ST-cut quartz substrates for space applications [10] was also taken into account. As for transducers, a group-type transducer [13], [14] was employed. The group-type transducer is advantageous from a fabrication point of view, since it cancels internal reflection within the transducer by using single electrodes, which are broader than commonly used double electrodes [5]. In fact, the width of the group-type transducer electrodes for the fabricated SAW filters is 0.51 μm, which is compared to that of as narrow as 0.26 μm for double electrodes. With regard to weighting methods of the transducers, a withdrawal method was used in both the input and output transducers. In the withdrawal method, weighting is introduced by selectively withdrawing electrodes to equate the number of electrodes locally present with a desired weighting function [5]. The SAW filter chips were sealed in an inert atmosphere of nitrogen. Major parameters of the fabricated SAW bandpass filters are tabulated in Table I. Fig. 2 shows the fabricated SAW bandpass filter, in which a shielding electrode was placed between the input and output transducers.

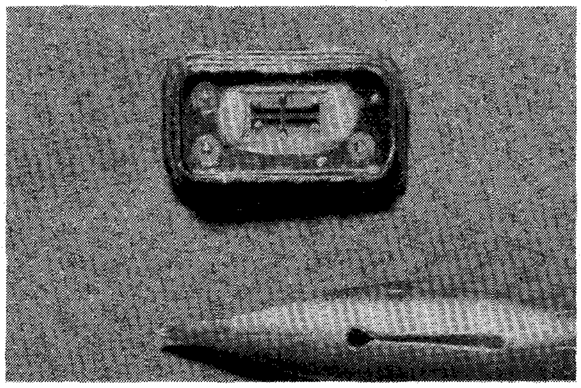


Fig. 2. Fabricated L-band SAW bandpass filter.

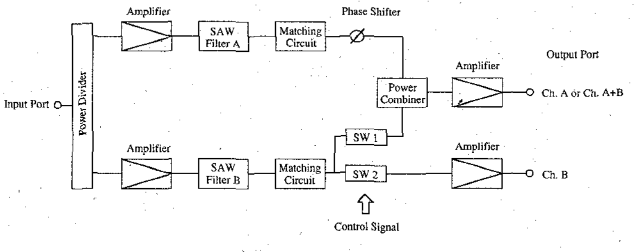


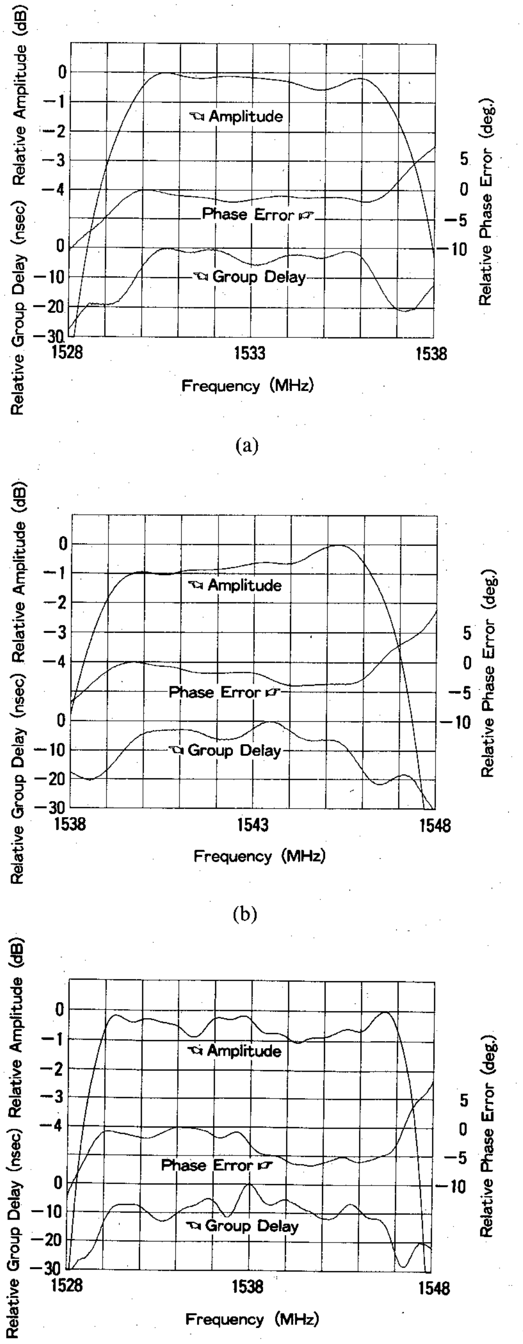
Fig. 3. Configuration of a two channel bandwidth-variable SAW filter bank.

These SAW bandpass filters were then assembled in a two channel bandwidth-variable SAW filter bank, shown

TABLE II
DESIGN OBJECTIVES OF INDIVIDUAL AND COMBINED CHANNELS

	Ch. A, Ch. B	Ch. A + B
1.5 dB Bandwidth (MHz)	<6.5	<16.0
Transition Bandwidth (MHz)	>3.0	>3.0
Amplitude Ripple* (dB p-p)	>1.2	>1.5
Phase Error* (deg. p-p)	>6.0	>10.0
Group Delay Ripple* (nsec p-p)	>30.0	>40.0
Worst Out-of-Band Rejection** (dB)	> −30.0	> −30.0

*—Measured within a 1.5 dB bandwidth. **—Measured over a span of 500 MHz.

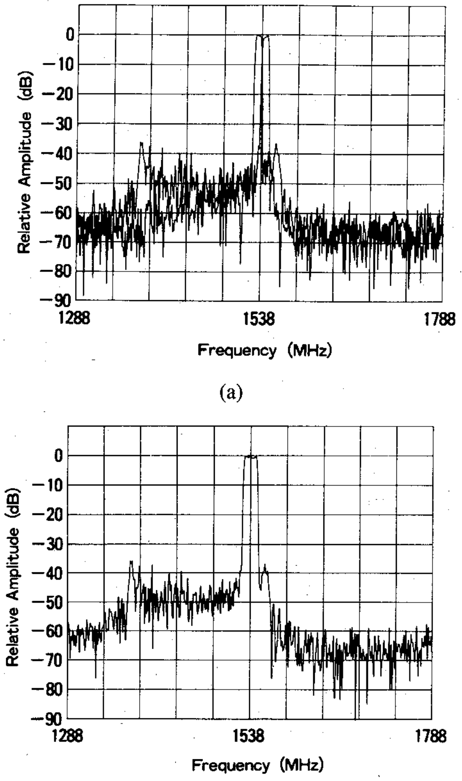


(a)

(b)

(c)

Fig. 4. Measured in-band responses of the two channel bandwidth-variable SAW filter bank. ((a) Ch. A, (b) Ch. B, (c) Ch. A + B)



(a)

(b)

Fig. 5. Measured out-of-band responses of the two channel bandwidth-variable SAW filter bank. ((a) Ch. A, Ch. B, (b) Ch. A + B)

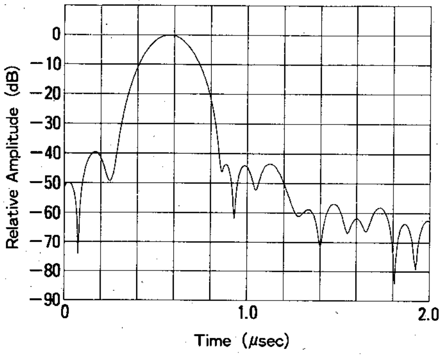


Fig. 6. Measured time domain response of Ch. A of the two channel bandwidth-variable SAW filter bank.

in Fig. 3, in order to demonstrate practicality. Two switches SW1, SW2 were used to control the channel combining. When SW1 is off and SW2 is on, two individual channels called Ch. A and Ch. B appear at the two output ports, whereas only a combined channel called Ch. A + B appears at one port when SW1 is on and SW2 is off. Design objectives of these channels are tabulated in Table II. Here, a passband is defined as the 1.5 dB bandwidth, and a transition bandwidth as the 1.5 to 30 dB bandwidth. For the design of SAW filters, more stringent objectives, e.g., broader passbands, narrower transition bandwidths and higher out-of-band rejection levels, were used in order to allow possible degradation caused by fabrication process, second-order effects [7], [15], design errors and stability characteristics.

TABLE III
MEASURED ELECTRICAL PERFORMANCE DATA OF TWO CHANNEL BANDWIDTH-VARIABLE SAW FILTER BANK

	Ch. A	Ch. B	Ch. A + B
Insertion Loss (dB)	−16.5	−17.1	−16.3
Center Frequency (MHz)	1533.22	1542.79	1537.98
1.5 dB Bandwidth (MHz)	7.42	7.23	16.85
Lower Transition Bandwidth (MHz)	2.52	2.96	2.57
Upper Transition Bandwidth (MHz)	2.76	2.68	2.78
Amplitude Ripple* (dB p-p)	0.6	1.0	1.1
Phase Error* (deg. p-p)	3.10	3.92	6.74
Group Delay Ripple* (nsec p-p)	19.65	23.60	31.87
Worst Out-of-Band Rejection in Lower Region** (dB)	−35.8	−36.0	−35.5
Worst Out-of-Band Rejection in Upper Region** (dB)	−39.4	−36.0	−36.9
Electromagnetic Feedthrough Level (dB)	−49.8	−57.0	−49.6
Triple Transit Echo Level (dB)	−58.2	−58.1	−63.2

*—Measured within a 1.5 dB bandwidth. **—Measured over a span of 500 MHz.

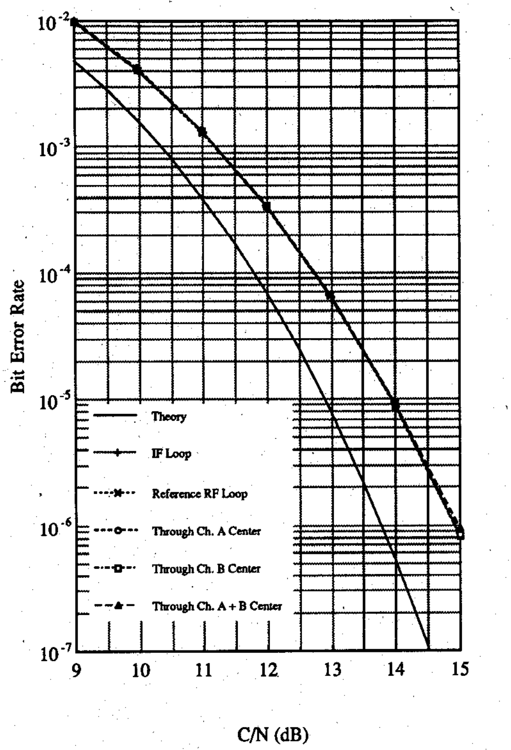


Fig. 7. Measured BER performance through the two channel bandwidth-variable SAW filter bank.

Measured in-band responses of the individual channels Ch. A, Ch. B and the combined channel Ch. A + B are shown in Fig. 4. The responses of the combined channel, Fig. 4(c), demonstrate the accurate design of the linear phase SAW bandpass filters at as high frequencies as the 1.5 GHz band. Good out-of-band rejection characteristics, at least −35 dB, were obtained over a wide frequency span of 500 MHz as shown in Fig. 5. Fig. 6 shows a time domain response of Ch. A, as an example. The electromagnetic feedthrough, monitored close to time 0 sec, was strongly suppressed by the use of a Ferrite transformer [5] at the output port of the SAW bandpass filter. The other harmful element, a triple transit echo (TTE) monitored at approximately 1.7 μsec which is three times the main SAW propagation time, was also strongly suppressed to approximately −58 dB relative to the main SAW power. The electromagnetic feedthrough level of Ch. A + B, −49.6 dB, was the worst value among all the feedthrough levels and TTE levels measured, but it produces amplitude and phase ripples as small as 0.06 dB p-p and 0.38 deg. p-p. Measured electrical performance data are tabulated in Table III, which indicates that the fabricated SAW filter bank meets all the design objectives shown in Table II.

In order to evaluate the effects of the fabricated SAW filter bank on a digital signal, a transmission experiment was conducted. A 1.544 Mbit/s differentially encoded quadrature phase shift keyed (QPSK) signal was transmitted through the center of Ch. A, Ch. B and Ch. A + B, and bit error rate (BER) performance was measured. Measured results are shown in Fig. 7, in which the BER performance in an RF loop without the SAW filter bank (reference RF loop) and in a modern loop (IF loop) is also shown for reference. As shown in Fig. 7, BER performance degradation introduced by the SAW filter bank is negligible even through the center of Ch. A + B, in which case the digital signal is first subdivided into lower and higher subbands and then re-combined.

III. TEMPERATURE AND AGING STABILITY CHARACTERISTICS

The ST-cut quartz substrate is one of the stable piezoelectric substrates found against temperature changes. The center frequency will be parabolically lowered and the phase will be parabolically lagged as a function of temperature changes from the turnover temperature of typically 25 to 30°C [13]. In the case of the bandwidth-variable SAW filter bank, however, the temperature stability characteristics of the whole bank are more important than those of the individual filters. Hence, the temperature stability characteristics of the fabricated SAW filter bank were measured under ambient temperatures of −15°C, +25°C and +55°C. Note that the components used for the SAW filter bank such as amplifiers are not temperature-stabilized ones.

Table IV summarizes the measured drifts from the data

TABLE IV
MEASURED DRIFTS FROM DATA MEASURED AT +25°C

	Ch. A	Ch. B	Ch. A + B
Insection Loss (dB)	−0.75	−0.59	−0.58
	−1.42	−1.27	−1.28
Center Frequency (kHz)	−54.6	+2.4	−10.5
	−118.4	−91.1	−29.8
1.5 dB Bandwidth (kHz)	+19.3	−39.7	−40.2
	+17.4	+51.8	+30.2
Lower Transition Bandwidth (kHz)	+41.9	+29.0	+114.7
	−50.5	−54.4	+28.4
Upper Transition Bandwidth (kHz)	+22.9	−43.0	−62.6
	−42.7	−11.7	−231.5
Amplitude Ripple* (dB p-p)	−0.06	+0.03	+0.01
	+0.00	−0.12	−0.05
Group Delay Ripple* (nsec p-p)	+0.67	−0.99	−8.79
	−0.35	+0.61	+6.55
Worst Out-of-Band Rejection in Lower Region** (dB)	−0.58	−2.61	−0.57
	+1.61	−0.98	+1.73
Worst Out-of-Band Rejection in Upper Region** (dB)	−0.15	+1.36	+1.96
	+2.38	−1.16	−0.44

Upper figures correspond to drifts at −15°C, and lower ones at +55°C. *—Measured within a 1.5 dB bandwidth. **—Measured over a span of 500 MHz.

measured at +25°C. With regard to the drifts of the passbands and the transition bandwidths, those of −40.2 to +51.8 kHz and −231.5 to +114.7 kHz were observed, respectively. The passbands and the transition bandwidths of all the channels still met the design objectives shown in Table II in all temperatures, because the passbands were designed wider and the transition bandwidths were designed narrower than the design objectives to allow these drifts. Regarding the amplitude ripples, it is noteworthy that the drift in Ch. A + B was negligibly small as +0.01 dB at −15°C and −0.05 dB at +55°C despite the amplifiers used, which were not temperature stabilized. This result demonstrates strongly correlated gain drifts of the separate amplifiers contained in the Ch. A and Ch. B routes. The group delay ripples were within the design objectives in all temperatures. The worst out-of-band rejection levels were always less than the design objective of −30 dB with a margin of at least 3.8 dB in all temperatures. As we have seen, satisfactory temperature stability characteristics of the microwave bandwidth-variable SAW filter bank would be obtained, if ST-cut quartz was used as a piezoelectric substrate for the SAW filters and stringent specifications to allow expected drifts were adopted at the SAW filter design stage.

We now consider the aging stability characteristics of the bandwidth-variable SAW filter bank. The aging stability characteristics of SAW filters are known to be affected by the treatment of the crystal in preparation, mounting and packaging as well as piezoelectric substrate materials [7]. Since the aging data of the fabricated SAW bandpass filters were not available, the aging stability characteristics were estimated based on the aging data of 125 MHz ST-cut quartz SAW bandpass filters employing the same kind of crystal treatment, mounting and packaging. The aging data were measured in an accelerated test (120°C, 10 000 hours) and in a temperature cycle test (−10 to +70°C, 6 hours/cycle, 1400 hours). Center frequency drifts of 41 ppm p-p were measured during in an accelerated test, and those of 31 ppm p-p were measured during in a temperature cycle test. Based on these data, center frequency drifts of ±50 ppm were assumed as the aging stability characteristics of the Ch. A and Ch. B routes in a 15 year satellite life time. With regard to insertion loss or gain drifts by aging, those of SAW filters as well as those of associated amplifiers should be taken into account. Two feedback type amplifiers were assumed to be connected to each SAW bandpass filter. Measured gain drifts of aforementioned SAW bandpass filters and those of two feedback type amplifiers are shown below.

	Accelerated Test	Temperature Cycle Test
SAW filter	0.22 dB p-p	0.17 dB p-p
Two amplifiers	0.20 dB p-p	0.10 dB p-p

Based on the above data, gain drifts of 0.36 dB p-p, an rms value of the data shown above, were assumed as the gain stability characteristics of the Ch. A and Ch. B routes in a 15 year satellite life time.

For the individual channels Ch. A, Ch. B, the aging stability characteristics would be insignificant if the SAW bandpass filters were designed to have broader passbands and narrower transition bandwidths as shown in Table III to allow the frequency drifts by aging. Hence, calculations were made to assess the aging stability characteristics of Ch. A + B. In the calculations, it was assumed

TABLE V
CALCULATED DRIFTS OF CH. A + B BY AGING STABILITY CHARACTERISTICS

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
	$f_A - 77$ kHz $f_B + 77$ kHz	$f_A + 77$ kHz $f_B - 77$ kHz	$f_A - 77$ kHz $f_B + 77$ kHz $g_B + 0.36$ dB	$f_A - 77$ kHz $f_B + 77$ kHz $g_B - 0.36$ dB	$f_A + 77$ kHz $f_B - 77$ kHz $g_B + 0.36$ dB	$f_A + 77$ kHz $f_B - 77$ kHz $g_B - 0.36$ dB
Center Frequency (kHz)	−2.0	+7.8	+74.9	−71.6	+92.7	−79.1
1.5 dB Bandwidth (kHz)	+153.7	−541.9	+0.6	+170.7	−533.0	−582.6
Lower Transition Bandwidth (kHz)	+8.2	+177.7	+147.5	−63.1	+253.3	+115.7
Upper Transition Bandwidth (kHz)	−4.2	+164.4	−10.0	+54.6	+80.0	+266.1
Amplitude Ripple* (dB)	−0.00	+0.44	+0.00	+0.15	+0.24	+0.66

*—Measured within a 1.5 dB bandwidth.

that the center frequencies of Ch. A and Ch. B, designated as f_A, f_B, drifted in opposite directions by 77 kHz (corresponding to 50 ppm), and that the gain of Ch. B, designated as g_B, drifted by +0.36 or −0.36 dB relative to that of Ch. A in order to assess the worst cases. Furthermore, only the effects on the amplitude responses were calculated using the measured amplitude responses of Ch. A and Ch. B at +25°C, assuming the phase responses were ideal. Table V summarizes the calculated drifts of Ch. A + B for worst six cases, defined on the first row. Broader passbands were resulted in Cases (1), (3) and (4), in which Ch. A and Ch. B drifted to separate, while narrower passbands in Cases (2), (5) and (6), where two channels drifted to approach. The passbands of all the cases still met the design objective of 16.0 MHz. The drifts in the transition bandwidths were −63.1 to +266.1 kHz. Only the upper transition bandwidth in Case (6) could not meet the design objective of 3 MHz slightly by 50 kHz. Regarding the effects on the amplitude ripples, Case (6) suffered the maximum drift of +0.66 dB, and could not meet the design objective slightly by 0.2 dB. The amplitude ripple even in this case would be improved at least by 0.5 dB by a proper adjustment of the matching circuit of Ch. B. As stated above, satisfactory aging stability characteristics of the microwave bandwidth-variable SAW filter bank would be obtained if stringent specifications to allow the drifts by aging were adopted at the SAW filter design stage. Since the study shown here assumed the aging stability characteristics of the microwave bandwidth-variable SAW filter bank based on the aging data of IF SAW bandpass filters, measurements of the aging data using the microwave SAW bandpass filters are highly essential hereafter. Note also that the probability that the investigated worst cases will occur is low.

IV. CONCLUSIONS

Microwave SAW bandpass filters were discussed for spacecraft applications in this paper. Two SAW bandpass filters were designed and fabricated in the 1.5 GHz band using temperature-stable ST-cut quartz substrates, and then assembled in a two channel bandwidth-variable SAW filter bank to demonstrate practicality. Measured electrical responses as well as results of a transmission experiment showed satisfactory performance. Effects of the temperature and aging stability characteristics were discussed based on the measured and calculated responses. It was concluded that the satisfactory stability characteristics would be obtained if ST-cut quartz was used as a piezoelectric substrate for the SAW filters and stringent specifications were adopted at the SAW filter design stage to allow expected drifts. A distinct disadvantage of the microwave SAW bandpass filters is their high insertion losses. However, this drawback would be solved by the proper design of transponders with acceptable dc power consumption, especially in the design of G/T's and level diagrams. As a consequence, microwave SAW bandpass filters would be used in future spacecraft as microwave bandpass filters with sharp frequency selectivity, a linear phase response and/or a high out-of-band rejection level, or for a microwave multiplexer having contiguous channels, whose bandwidths can be changed on demand.

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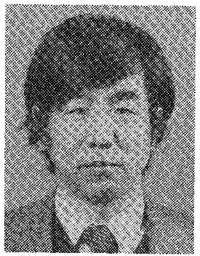

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