SAW Bandpass Filter Design for 1.6-GHz PCM Timing Tank Applications

JIRO TEMMYO AND SHOKICHIRO YOSHIKAWA

***Abstract*—A 1.6-GHz surface acoustic wave (SAW) timing tank for a self-timed regenerative repeater for an ultrahigh-speed PCM optical fiber transmission system is described. A SAW narrow bandpass filter with 0.74-μm linewidth interdigital transducers with double electrode geometry and 20-nm aluminum metallization on AT-quartz substrate is realized by conventional optical photolithography. Typical performance obtained is as follows: center frequency f_0 is 1.5993 GHz; insertion loss is 22 dB; stopband attenuation is above 23 dB with respect to the passband; stability is $|2Q_L \cdot \Delta f/f_0| < 0.1$, where Q_L is loaded Q value and Δf is mistuning due to temperature effects. It is demonstrated that SAW quartz transversal filters can be made into new practical filters which have both high Q value and high stability in the GHz range and are satisfactory from the standpoints of precise design, fabrication technique, and performance.**

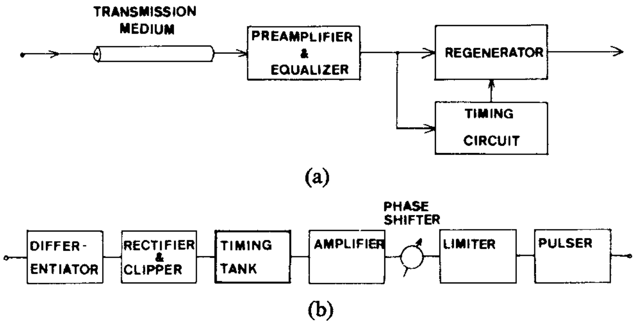

Fig. 1. Block schematics. (a) Pulse transmission link in PCM. (b) Timing circuit for nonlinear extraction.

I. Introduction

The surface acoustic wave (SAW) quartz filters and oscillators are useful for new practical communications applications because of their simplicity, compactness, high stability, good reproducibility, and low production cost. In this paper, as one practical system application of GHz SAW devices, a 1.6-GHz SAW quartz narrow bandpass filter to be used as a timing tank for a self-timed regenerative repeater for an ultrahigh-speed 1.6-Gbit/s PCM optical fiber transmission is described.

One feature of PCM transmission is that the pulse train can be regenerated by regenerative repeaters after it has traveled through a dispersive, noisy medium. Such repeaters must accomplish three basic functions—reshaping, retiming, and regeneration. This operational breakdown is depicted schematically in Fig. 1(a), where the pulse train is traced from repeater to repeater [1]. Timing plays an important role in PCM transmission. Self-timed transmission, where the timing wave is obtained by processing the information-bearing pulse train by linear or nonlinear means or both, is used widely in present PCM transmission systems. Several circuit configurations for timing wave extraction have been investigated. In general, the timing circuit for nonlinear extraction consists of the elements shown in Fig. 1(b): a differentiator, full-wave rectifier, tank circuit tuned to the repetition rate, etc. By far the simplest and cheapest tank circuit is the single-tuned LC tank. Currently, LC resonators such as loaded cavities with inductive loops for input and output coupling [2], helical resonators and spiral resonators with typical loaded Q of 100, quartz filters, and phase-locked timing extraction circuits [3] are used in coaxial PCM systems with bit rates below 400 Mbit/s. Phase-locked timing extraction circuits have effective Q values high enough (up to 10^6) to sufficiently suppress systematic jitter in long chains of PCM repeaters.

Experimental SAW timing tanks [4], [5] utilizing the fundamental mode which have been studied in 400-Mbit/s PCM coaxial and/or optical fiber transmission system repeaters have exhibited high temperature stability and relatively high Q characteristics. The Q values of SAW filters can be between those of LC resonators and phase-locked timing circuits. The inherent delay in SAW filters has been found to reduce the systematic jitter in long chains of PCM repeaters [4]. A PCM coaxial transmission experiment involving speeds up to 1.2 Gbit/s has been done employing a strip line resonator [6] with loaded Q of 100. Recently, experimental 1.6-Gbit/s PCM optical fiber transmission has also been successfully achieved [7]. For accurate timing-wave regeneration, tank Q values should be as high as possible, especially for optical fiber transmission systems. It has recently been found that 2-GHz SAW quartz transversal filters can be easily realized with optical photolithography [8]. GHz SAW quartz narrow bandpass filters are advantageous because of their small size, high stability, and high Q values, comparing with other conventional passive devices.

This paper presents results obtained with a 1.6-GHz timing tank employing a SAW quartz third harmonic transversal filter, which is utilized in a self-timed regenerative repeater to realize 1.6-Gbit/s PCM optical fiber transmission. Section II gives design considerations for a 1.6-GHz SAW timing tank. Section III describes SAW

Manuscript received December 10, 1979; revised February 7, 1980.
J. Temmyo is with the Musashino Electrical Communication Laboratory, Nippon Telegraph and Telephone Public Corporation, 3-9-11, Midoricho, Musashion-Shi, Tokyo 180, Japan (0422) 59-2392.
S. Yoshikawa was with the Musashino Electrical Communication Laboratory, Tokyo, Japan. He is now with the Electrical and Electronics Systems Engineering Course, The Technological University of Nagaokata, Kamitomiokacho, Nagaoka-shi, Niigata 949-54, Japan (0258)46-6000.

0018-9480/80/0800-0846$00.75 ©1980 IEEE

device fabrication. Section IV presents the performance of the SAW timing tank in detail.

II. Design

A. Basic Considerations

There are several sources of timing jitter and mistiming in self-timed regenerative repeaters using LC tanks for timing recovery [1]: 1) finite pulsewidth and pattern effects; 2) thermal and impulse noise; 3) crosstalk; 4) mistuning; and 5) nonlinear amplitude-to-phase conversion. The output of the timing tank is thus a sinusoidal signal at the pulse repetition frequency with random modulation of both amplitude and phase. Random modulation occurs because of noise, the statistical nature of the signal variations in the pulse positions from the required spacing, and tuning error in the resonant circuit. This random modulation is dependent upon the bandwidth of the resonant circuit. The higher the selectivity quality factor Q (unloaded Q value), the narrower the bandwidth of the resonant circuit and, therefore, the greater the suppression of unwanted position modulation. Static phase errors can arise due to mistuning of the resonant circuit. The phase shift variation $\Delta\phi$ for conventional LC resonators is given by [2]

$$\Delta\phi = 2Q_L(\Delta f/f_0) \tag{1}$$

for small values of Δf, where f_0 is the resonant frequency, Q_L the loaded Q value, and Δf mistuning, which is mainly due to temperature variation and aging effects. Timing tank phase shift with frequency is an important characteristic and must be as small as possible, typically under $\pm 5.7°$ [2], because the variation disturbs timing information, causing the pulsetrain phase to vary and the signal error rate to increase. From (1), the allowable resonant frequency error for a given amount of timing wave phase shift is inversely proportional to Q_L. This means that the Q_L chosen must be a compromise between the amount of retiming and the stability requirements of the tank circuit. A Q_L of about 100 is practical to implement and appears to meet both requirements for exchange area systems. On the other hand, the jitter in long chains of repeaters is caused mainly by systematic jitter sources related to the pattern, with mistuning apparently not a major contributor. Here, timing jitter power is proportional to the timing filter bandwidth, so high Q_L tank circuits in the repeater reduce the jitter [9]. Accordingly, timing tanks with both high Q_L and high stability (i.e., lower mistuning) are preferable.

Next, consider the use of SAW transversal filters as a timing tank. The transfer function $H_p(f)$ of a SAW harmonic transversal filter with two identical unapodized interdigital transducers (IDT's) for the pth harmonic mode near the pth center frequency f_p is given by the following:

$$H_p(f) \alpha \frac{\sin^2 x}{x^2} \exp(-j2\pi f \tau_D) \tag{2}$$

$$x = p\pi N \frac{f - f_p}{f_p} \tag{3}$$

where N is the number of IDT pairs and τ_D is the filter delay time. Accordingly, the relative 3-dB bandwidth for the SAW filter is given by

$$\frac{\delta f}{f_p} = \frac{2}{p\pi N}. \tag{4}$$

Here, for convenience, $Q_{3\text{ dB}}$ value is defined by

$$Q_{3\text{ dB}} \equiv \frac{f_p}{\delta f}. \tag{5}$$

The phase shift variation $\Delta\phi_{SAW}$ with frequency for a SAW harmonic filter with propagation length L_D, which is defined as the distance between the centers of input and output transducers which have constant pitch length, is given by

$$\begin{aligned}\Delta\phi_{SAW} &= 2p\pi M(\Delta\tau_D/\tau_D)\\ &= 2p\pi M(\Delta f/f_0)\end{aligned} \tag{6}$$

where SAW propagation length L_D is equal to M times the SAW fundamental wavelength λ_S. Here, $\Delta\tau_D$ is delay time change and Δf is frequency variation.

Next, the effective Q value $Q_{\text{eff},p}$ for the SAW pth harmonic filter is defined by [8]

$$Q_{\text{eff},p} \equiv p\pi M. \tag{7}$$

Therefore, the phase shift variation $\Delta\phi_{SAW}$ can be described as follows:

$$\Delta\phi_{SAW} = 2Q_{\text{eff},p}(\Delta f/f_p). \tag{8}$$

By comparing the expressions in (1) and (8), it is seen that the $Q_{\text{eff},p}$ value in SAW transversal filters corresponds to the loaded Q value Q_L in LC resonators. If the number N of input and output IDT finger pairs is equal to the wavenumber M, $Q_{\text{eff},p}$ is accurate to twice the value of $Q_{3\text{ dB}}$. This gives the following relation in SAW transversal filters:

$$Q_{\text{eff},p} \geqslant 2Q_{3\text{ dB}}. \tag{9}$$

Thus $Q_{\text{eff},p} = 2Q_{3\text{ dB}}$ is preferable to give high-frequency stability in SAW transversal filter designs for timing tank applications. Here, it should also be noted that in general the $Q_{3\text{ dB}}$ value (i.e., unloaded Q value), which can be measured by a network analyzer in a 50-Ω system, is quite different from the effective Q value $Q_{\text{eff},p}$ in SAW transversal harmonic filters. This is in contrast to high Q SAW resonators and LC resonators, for which the $Q_{3\text{ dB}}$ value is nearly equal to the loaded Q value. In summary, the effective Q value $Q_{\text{eff},p}$ corresponding to the loaded Q value or wavenumber M (filter delay time) is related to filter phase stability as expressed in (7) and (8).

In order to realize both high $Q_{3\text{ dB}}$ value amd small phase shift variation, delay time temperature change $\Delta\tau_D$ must be as small as possible. Therefore, the SAW filter substrate chosen is rotated Y-cut quartz near ST-cut whose second-order temperature coefficient of delay time is extremely small: 31×10^{-9}°C^{-2}. SAW quartz filters are much more stable with respect to aging than LC resonators. Therefore, SAW quartz filters can simultaneously satisfy the requirements for high $Q_{3\text{ dB}}$ and small temperature phase shift variation without difficulty. This makes it

TABLE I
1.6-GHz TIMING TANK SPECIFICATIONS IN A 50-Ω SYSTEM

Center frequency f_0	1.599997 GHz
Insertion loss	20 dB
Q_{3dB}	800-1500
Stability (Phase shift variation $\Delta\phi$)	$\Delta\phi < \pm 0.1$ $< \pm 5.7°$
stopband attenuation	23 dB

clear that SAW narrow bandpass filters are superior as timing tanks to *LC* resonators in the GHz region. A detailed discussion on the exact design for center frequency and insertion loss is presented in the next section.

Typical specifications [10] for a timing tank for a 1.6-Gbit/s PCM optical fiber transmission system are shown in Table I. These goal values were determined from actual 1.6-Gbit/s PCM transmission experimental conditions. For example, the tank center frequency chosen, 1.599997 GHz, is a harmonic frequency of the multiplied quartz oscillators used in carrier signal generators. The tank $Q_{3\text{ dB}}$ and stopband attenuation values, which are related to the timing jitter (especially low-frequency systematic jitter power), and the stability value were determined by analogy to successful PCM transmission experiments in long chains of repeaters at lower bit rates [2], [11], [12]. Tank insertion loss is not so critical in PCM applications because a low-noise amplifier is used after the tank circuit.

B. Design Details

The third harmonic mode of an IDT with double electrode geometry was used to realize 1.6-GHz narrow bandpass performance in order to minimize phase distortion and facilitate IDT fabrication. The transducer linewidth chosen was 0.74 µm, the input and output transducers, both unapodized, had 168 pairs. Propagation length L_D, which is defined as the distance between the centers of the transducers, is equal to the IDT length $168\lambda_s$. These pattern parameters result in a SAW filter with $Q_{3\text{ dB}}=800$ and $Q_{\text{eff},3}$ (i.e., Q_L) = 1600. Accordingly, the required 23-dB stopband attenuation is easily achieved by adopting unapodized input and output transducers with the same number of IDT pairs.

In order to achieve SAW filters with a center frequency at 1.599997 GHz and turnover temperature of 30°C, the quartz was precisely AT-cut, propagation direction φ_p from the X axis was 9°, and transducer Al-film thickness was 20 nm. These values were determined by considering velocity dispersion in Al-film IDT's with double electrode geometry [8] and estimating the turnover temperature shift caused by the Al-film IDT in the propagation path [13].

Next, let us consider 1.6-GHz SAW filter insertion loss. In the GHz range, it is necessary to consider stray capacitance C_p and finger resistance R_E caused by using thin Al-film and narrow linewidth. The only transducer conversion loss (CL) considered here is that which results from mismatch between the signal source (or load) and

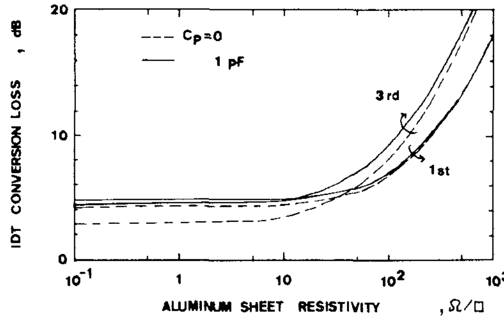

Fig. 2. Relation between calculated IDT conversion loss CL and aluminum sheet resistivity for the IDT fundamental and third harmonic modes on AT-quartz, where C_p is stray capacitance. IDT geometry is double electrode. IDT pairs: 168, linewidth a_L: 0.74 µm, aperture w: 0.185 mm, metallization thickness t: 20 nm.

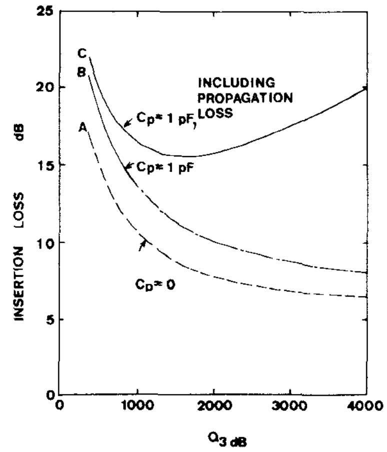

Fig. 3. Calculated insertion loss versus $Q_{3\text{ dB}}$ value for 1.6-GHz SAW filter with input and output IDT's on AT-quartz employing the third harmonic mode. IDT geometry is double electrode. Curve A is the ideal case corresponding to $C_p=0$ and $R_E=0$ with no propagation, beam steering, or diffraction losses. Curve B includes only stray capacitance effects. Curve C includes stray capacitance effects and propagation losses.

the transducer and finger resistance. Fig. 2 shows calculated transducer CL values for transducer fundamental and third harmonic modes versus aluminum sheet resistivity. These CL values were calculated utilizing Smith's equivalent circuit, which was modified for higher harmonic modes [8]. The transducer aperture was chosen so that the transducer third harmonic CL is minimum relative to other passband CL values for the ideal case corresponding to $C_p=0$ and $R_E=0$. It is found that stray capacitance, which was measured as 1 pF, makes CL increase considerably. On the other hand, it is also found that measured aluminum sheet resistivity, 2.1 Ω/□, which yields transducer finger resistance R_E of 1.5 Ω, does not cause a serious increase in CL because the $Q_{3\text{ dB}}$ value of the present SAW filter is relatively large. In general, SAW filter insertion loss is given by

$$\text{IL(dB)} = \text{CL}_{\text{in}} + \text{CL}_{\text{out}} + 6 \tag{10}$$

where 6 dB is the loss caused by IDT bidirectionality. Here, CL_{in} and CL_{out} are input and output transducer CL values. In addition, for GHz SAW devices, propagation loss L_p and, for the present filter, beam steering loss L_B

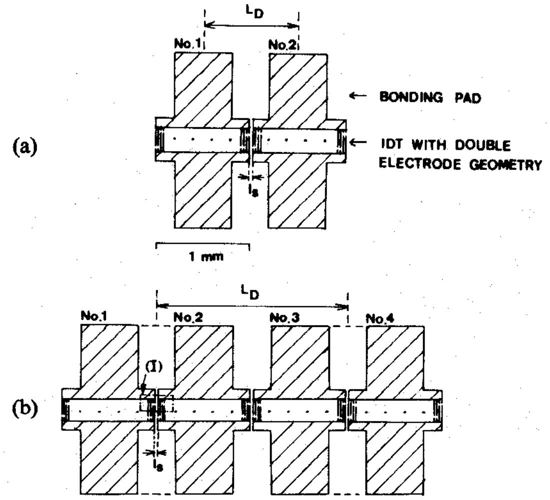

Fig. 4. Photomask patterns for a 1.6-GHz SAW timing tank. (a) $Q_{3\,\mathrm{dB}}=800$ and $Q_{\mathrm{eff},\,3}=1600$. (b) $Q_{3\,\mathrm{dB}}=1600$ and $Q_{\mathrm{eff},\,3}=3200$.

must be considered. For the present device, L_p was estimated using Budreau's experimental formula [14] as 2.3 dB and L_B was calculated as 1.8 dB for $\varphi_p=9°$. Considering the above total losses, the IL value for a 1.6-GHz SAW timing tank is estimated as 19.5 dB.

The relation between the IL values of 1.6-GHz SAW quartz transversal harmonic filters utilizing the third harmonic passband of IDT with double electrode geometry and the $Q_{3\,\mathrm{dB}}$ values of the filters is shown in Fig. 3 where IDT finger resistance can be neglected because of the relatively high $Q_{3\,\mathrm{dB}}$ values and beam steering loss is neglected. This figure shows that 1.6-GHz SAW filter IL has a minimum near $Q_{3\,\mathrm{dB}}=1600$, where IL is largely caused by propagation loss in the 1.6-GHz band.

However, due to the present photolithography fabrication limitations concerning maximum achievable pattern area, discussed in the next section, the SAW filter with $Q_{3\,\mathrm{dB}}=800$ is mainly considered.

III. Fabrication

Aluminum metallization 0.74-μm linewidth transducers were fabricated by conventional contact printing without using lift-off process, using photomasks prepared by optical projection printing.

However, with the present optical projection printing techniques, some limitations exist: IDT maximum pattern area is 1×1 mm; IDT minimum achievable linewidth is 0.4–0.5 μm; and the minimum step of the pattern generator used to make reticles is 1 μm, which results in a minimum step of 0.01 μm in the final photomask after 1/100 photo-reduction process.

Transducer patterns of photomasks for SAW filters with $Q_{3\,\mathrm{dB}}$ of 800 and 1600 are shown in Fig. 4(a) and (b), respectively. Photomasks were fabricated by optical projection printing using an Electromask image repeater with a 1/10 Zeiss reduction lens. The total reduction ratio for obtaining the final photomasks was 1/100. These patterns consist of two or four IDT blocks separated by distance $l_s=0.74$ μm (equal to the IDT linewidth). The pattern length of each IDT is about 1mm, which is the maximum

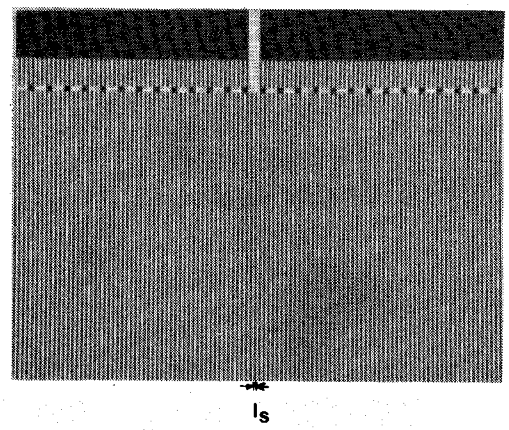

Fig. 5. Expanded view of area (I) in Fig. 4.

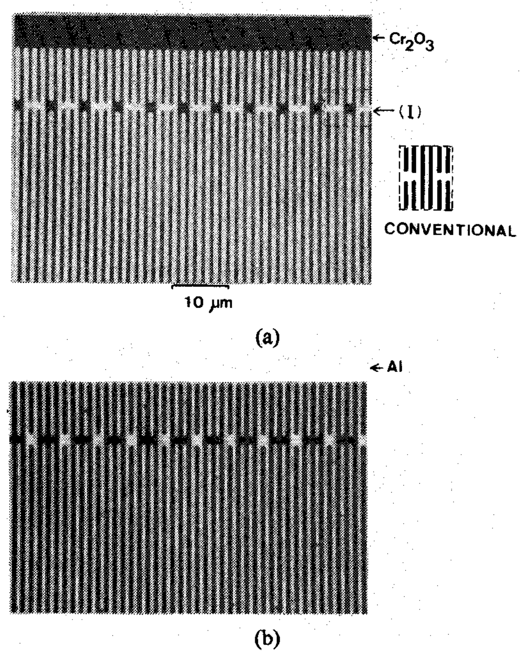

Fig. 6. Expanded view of (a) 0.74-μm linewidth IDT photomask prepared by optical projection printing, (b) 0.74-μm linewidth IDT with 20-nm aluminum metallization fabricated by contact printing, utilizing the photomask in Fig. 6(a).

value for fabrication by the present projection printing. However, if separation l_s actually has the designed value, precise pattern composition in the submicron region becomes possible: e.g., when IDT's No. 1 and No. 2 in Fig. 4(b) are connected with each other in parallel (as shown with dashed lines), an IDT with twice the $Q_{3\,\mathrm{dB}}$ value of IDT No. 1 can be obtained. In practice, it was confirmed experimentally that accurate pattern composition can be successfully achieved, because $l_s=0.74$ μm was obtained accurately, as shown in Fig. 5.

In fabricating the photomask transducer pattern, some compensatory corrections are required as shown in Fig. 6(a) to avoid disconnections in area (I), which can occur because of diffraction when the pattern is formed by optical projection printing [13]. Thin-film of Cr_2O_3 with the very low reflection index of 0.1 on glass substrate ($6.35\times6.35\times0.23$ cm) was useful for precise fine pattern formation.

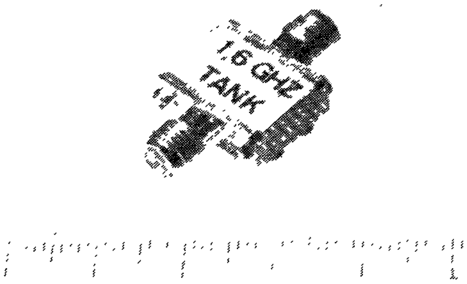

Fig. 7. 1.6-GHz timing tank.

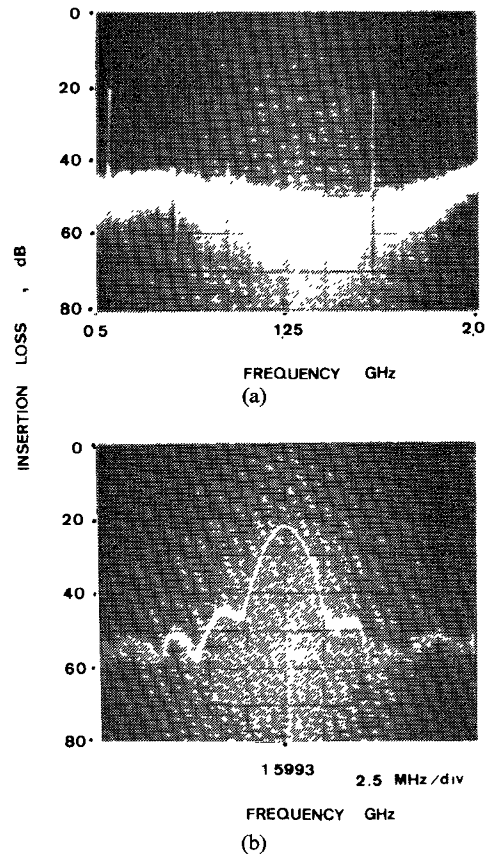

Fig. 8. Measured 1.6-GHz SAW timing tank frequency response with $Q_{3\ \mathrm{dB}}=800$. (a) Over the 0.5–2-GHz range. (b) Near the center frequency.

The photolithographic process by contact printing is as follows: the photomask is thicker than usual and the substrate size is sufficiently small ($4\times8\times0.2$ mm) to realize good contact between photomask and substrate during exposure with *i*-line UV light. Both IDT patterns in Fig. 4 were successfully transferred onto photoresist AZ 1350 film on AT-quartz with aluminum metallization. After development, the aluminum was etched by a chemical wet process and objective SAW IDT patterns with 20-nm metallization were obtained, as shown in Fig. 6(b). A photograph of the SAW timing tank is shown in Fig. 7.

IV. Characteristics

Fig. 8(a) and (b) shows the overall frequency response in a 50-Ω system over the 0.5–2.0-GHz range and in detail at the third harmonic passband near the center frequency $f_0=1.6$ GHz of a SAW filter with $Q_{3\ \mathrm{dB}}=800$. Inband ripple due to multiple transit echoes is greatly suppressed. Accordingly, good linearity of frequency phase characteristics was obtained. Stopband attenuation is above 23 dB. Here, bulk modes are found to be suppressed due to the choice of propagation direction $\varphi_p=9°$. The 3-dB bandwidth δf is found to be 2 MHz, as designed. The IL at 1.6 GHz is 22 dB, which is slightly larger than the calculated value. Center frequency f_0 is 1.5993 GHz. The small difference between the measured and designed f_0 values is caused by minor inaccuracies in fabrication, such as slight errors in exact propagation direction setting and fine IDT linewidth control. Fig. 9(a) shows a Smith Chart impedance display of the transducer over a 25-MHz range near 1.6 GHz. By achieving 50-Ω matching at 1.6 GHz using the triple-stub tuning technique for the transducer including the connector and bonding wire impedances, as shown with trace (b) in Fig. 9, the SAW filter insertion loss is reduced to 18 dB, a 4-dB improvement.

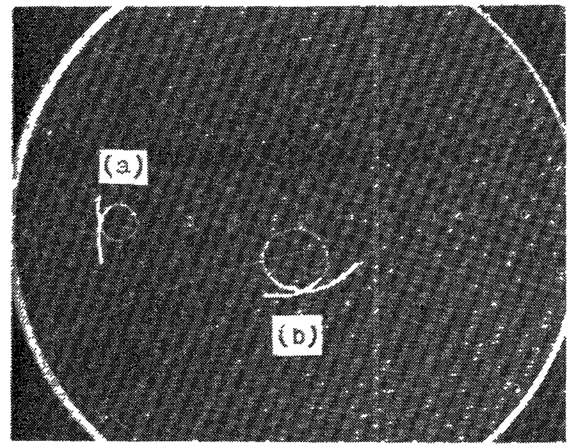

Fig. 9. Transducer input impedance displayed on a Smith Chart. Frequency sweeps over a 25-MHz range near 1.6 GHz. (a) "Bare" IDT with double electrode geometry on AT-quartz. (b) The same IDT in a packaged SAW filter matched to 50-Ω impedance at 1.6 GHz employing the triple-stub tuning technique.

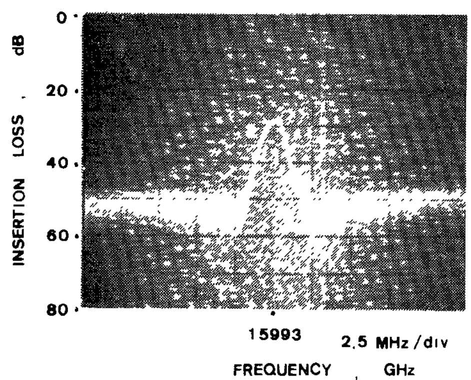

Fig. 10. Measured 1.6-GHz SAW timing tank frequency response with $Q_{3\ \mathrm{dB}}=1600$ and $Q_{\mathrm{eff},3}=3200$ near center frequency.

The performance of the 1.6-GHz SAW filter with $Q_{3\ \mathrm{dB}}=1600$ and $Q_{\mathrm{eff},3}=3200$ (Fig. 4(b)) is shown in Fig. 10. Its IL value is bigger than IL of the filter with $Q_{3\ \mathrm{dB}}=800$ because the IDT aperture has the same value as

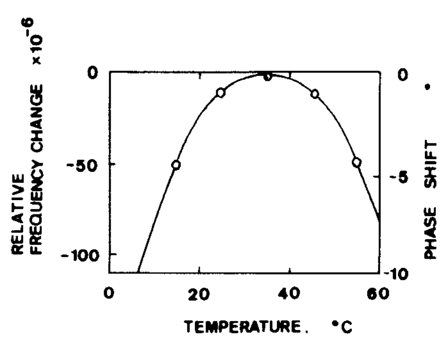

Fig. 11. Frequency change and/or phase shift change versus temperature variation for 1.6-GHz SAW timing tank with $Q_{3\,\mathrm{dB}}=800$.

the pattern with $Q_{3\,\mathrm{dB}}=800$, which is not the optimum value for minimizing IL in a SAW filter with $Q_{3\,\mathrm{dB}}=1600$.

The presence of the SAW filter fundamental passband is not a serious problem, because a selective amplifier and limiter are used after the tank in the practical system application, as shown in Fig. 1(b).

Next, Fig. 11 shows the relation between frequency change and/or phase shift and temperature variation. The turnover temperature is about 30°C, as designed, and the second-order temperature coefficient C_2 is -100×10^{-9}°C^{-2}, which was a slightly larger value than the X-axis direction propagation characteristic. The SAW propagation direction angle from the X axis has become larger and the experimental second-order coefficient has increased. These experimental results have not been clarified by theoretical calculations because of uncertainty about the temperature coefficients for quartz elastic stiffness. Relative frequency change $\Delta f/f_0$ is less than 100×10^{-6} ($\pm50\times10^{-6}$). Phase shift variation is less than 10° (±5°) in the 10–60°C range, which meets the specification of ±5.7°. To summarize the experimental results above, the present SAW quartz narrow bandpass filter satisfies most of the specifications in Table I.

At present, a 1.6-Gbit/s PCM single mode optical fiber transmission experiment employing the present device is successfully under test; the results are reported in detail elsewhere [15].

V. Conclusion

A 1.6-GHz SAW timing tank for a self-timed regenerative repeater in an ultrahigh-speed PCM optical fiber transmission system was realized. The SAW filter, using AT-quartz and 0.74-μm linewidth IDT with double electrode geometry and 20-nm aluminum metallization prepared by photolithography has shown both high Q and good phase shift stability performance in the GHz region simultaneously, something difficult to realize with other devices. Accordingly, it was shown experimentally for the first time that GHz SAW quartz transversal filters can become new practical communication devices from the standpoints of precise design, fabrication techniques, and performance.

Acknowledgment

The authors wish to thank Dr. K. Noda and Dr. Y. Kuroyanagi for their guidance and encouragement. They also thank Dr. T. Kimura and J. Yamada for their encouragement and suggestions concerning the specifications in Table I and Dr. J. Minowa and K. Hohkawa for stimulating discussions.

References

[1] Members of the Tech. Staff Bell Tel. Lab., *Transmission Systems for Communications*, 3rd ed., Bell Tel. Lab., Inc., 1964, ch. 26, pp. 658–677.

[2] I. Dorros, J. M. Sipress, and F. D. Waldhauer, "An experimental 224 Mb/s digital repeated line," *Bell Syst. Tech. J.*, vol. 45, pp. 993–1043, July 1966.

[3] F. D. Waldhauer, "A 2-level 274 Mb/s regenerative repeater for T4M," in *Conf. Rec. IEEE Int. Conf. Comm.*, pp. 48-13–48-17, June 1975.

[4] K. Nishikawa, "An improved surface acoustic wave filter for a PCM timing tank," in *1974 Ultrasonics Symp. Proc.*, pp. 164–167, Nov. 1974.

[5] J. Minowa, K. Nakagawa, K. Okuno, Y. Kobayashi, and M. Morimoto, "400 MHz SAW timing filter for optical fiber transmission systems," in *1978 Ultrasonics Symp. Proc.*, pp. 490–493, Sept. 1978.

[6] S. B. Cohen, "Direct-coupled-resonator filters," *Proc. IRE*, vol. 45, pp. 187–196, Feb. 1957.

[7] J. Yamada, S. Machida, H. Takata, and T. Kimura, "Dispersion-free single mode fiber transmission experiments up to 1.6 Gbit/s," *Electron. Lett.*, vol. 15, pp. 278–279, May 1979.

[8] J. Temmyo and S. Yoshikawa, "On the fabrication and performance of GHz SAW delay line filters for GHz SAW oscillators," *IEEE Trans. Sonics Ultrason.*, vol. SU-25, pp. 367–371, Nov. 1978.

[9] C. J. Byrne, B. J. Karafuin, and D. B. Robinson, Jr., "Systematic jitter in a chain of digital regenerators," *Bell Syst. Tech. J.*, vol. 42, pp. 2679–2714, Nov. 1963.

[10] J. Yamada and T. Kimura, private communication.

[11] T. Miki, H. Ishio, K. Nakagawa, and E. Yoneda, "Design and performance of the 32 Mb/s repeatered line for an experimental optical fiber transmission system," *ECL Tech. J.*, vol. 27, pp. 313–337, Feb. 1978.

[12] K. Nakagawa, Y. Okuno, Y. Matsumoto, and T. Umets, "An experimental 400 Mb/s optical repeater," in *Paper Tech. Group, Comm. Syst. IECE Jap.*, vol. CS 78-44, pp. 83–90, June 1978.

[13] J. Temmyo and S. Yoshikawa, "GHz SAW quartz transversal filters," *IEEE Trans. Sonics Ultrason.*, vol. SU-27, pp. 31–38, Jan. 1980.

[14] A. J. Budreau and P. H. Carr, "Temperature dependence of the attenuation of microwave frequency elastic surface-waves in quartz," *J. Appl. Phys.*, vol. 18, pp. 239–241, Mar. 1971.

[15] J. Yamada, J. Temmyo, S. Yoshikawa, and T. Kimura, "1.6 Gbit/s optical receiver at 1.3 μm with a SAW timing retrieval circuit," *Electron. Lett.*, vol. 16, pp. 57–58, Jan. 1980.