Design and Application of Wide-Band SAW Filters Using Slanted Finger Transducers

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Abstract

This paper describes the wide-band linear phase surface acoustic wave (SAW) filters composed of slanted finger transducers. To calculate the characteristics of slanted finger transducers, the transducers are divided to multiple channels. In each channel, amplitude and phase performance for the slanted fingers are approximated as that of normal fingers, and admittance matrix of each channel is calculated by applying Smith's equivalent circuit, after that, all the channels are connected in parallel one another. Two filters with 13% and 50% fractional bandwidths are designed using a finger pair weighting technique. Considering the features of the filters composed of the slanted finger transducers, that their pass-band characteristics can be controlled by changing the conditions of propagation path, filters having notches in the pass-band are studied. Fixed and variable notch filters with 50% fractional bandwidth are designed, and characteristics are verified by experiments.

1. Introduction

Filters having a wide fractional bandwidth can be built by combination of an apodized and an unapodized interdigital transducer (IDT), or by combination of two weighted transducers and a multistrip coupler (MSC). However, it is difficult for these filters to reduce the pass band ripple. On the other hand, the wide-band filters composed of slanted finger transducers are reported. In 1972, Daniel and de Klerk[1] compared the relative merits of the slanted finger transducers with those of the FM chirp and $\sin(x)/x$ apodization band pass filters. After 1980, C.K. Campbell et al. reported a few interesting papers[2~4]. But in these papers, two great advantages of the slanted finger transducers are not clarified. One of the advantage[5,6] of the slanted finger transducers is a possibility of obtaining the wide-band filters with low-loss and small-ripple pass-band, compared to the conventional filters. Another is the greater design fiexibility[7~9], such as shown in the variable filter design technique employing the subsidiary transducers located on the propagation path.

In this paper, two trial filters composed of the slanted finger transducers are shown, and realization of lower insertion loss and smaller pass-band ripple is confirmed. In addition, a fixed notch filter and a variable notch filter employing the techniques on the propagation path are demonstrated.

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2. Band pass filters

A slanted finger is not a conventional parallel electrode finger, but has such a construction that its width changes as shown in Figure 1. In this construction, the higher frequency SAW is excited by the short period part of the IDT, while the lower frequency SAW is excited by the long period part. As the electrode period determines the SAW frequency, a slanted finger transducer forms a band pass filter which has the pass band determined by the minimum and maximum period of the IDT.

2.1 Design principle

It is difficult to make an exact equivalent circuit of the slanted finger transducers. Therefore, its transmission channel is divided to some channels by the dotted lines parallel to the propagation axis as shown in Figure 1. In each channel, behavior of the slanted fingers are approximated as that of the normal fingers, and Smith's equivalent circuit is applied.

Finally, all the channels are connected in parallel one another, then the overall characteristics can be obtained.

(1) Division of the transmission path

Two methods[2] are used to divide the transmission path: One is the equal frequency division method and the other is the equal aperture division method.

For the equal frequency division method, the transmission path is divided in such a manner that the variation amount of the center frequency between adjacent channels becomes constant. For the equal aperture division method, the transmission path is divided in such a manner that the aperture length of all channels are equal. In both methods, the dimensions of divided channels are obtained geometrically. We define dimensions of the slanted finger transducer as shown in Figure 2.

Some parameters are denoted as follows;

S : Number of division

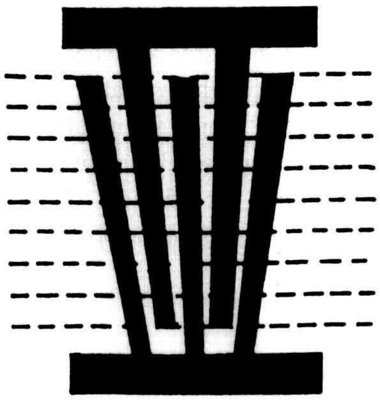


Fig. 1. A slanted finger transducer.

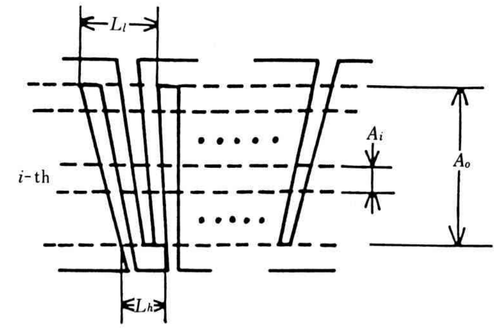


Fig. 2. Parameters.

L_l : Maximum period
L_h : Minimum period
A_0 : Aperture length of the transducer

The aperture length A_i and the center frequency f_i of the i-th channel are provided by the following equations.

For the equal frequency division method

$$f_i = f_l + i\frac{(f_h - f_l)}{S} \qquad i=1, 2, 3, \cdots, S$$
$$A_i = \frac{f_h \cdot f_l}{f_i \cdot S(f_i + f_h - f_l)} A_0 \tag{1}$$

For the equal aperture division method

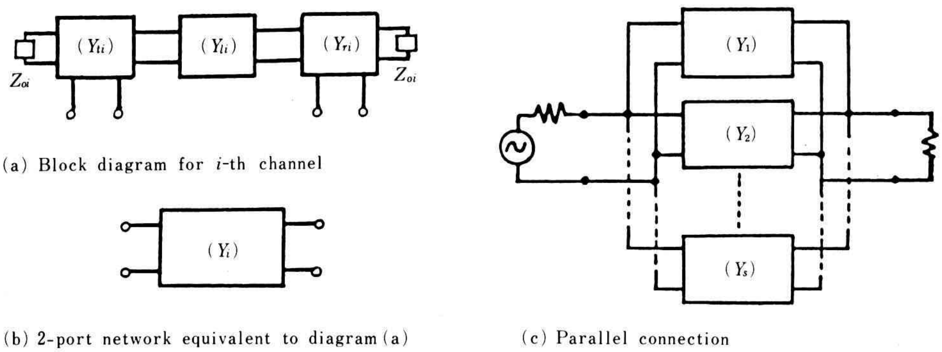
$$f_i = \frac{S \cdot f_h \cdot f_l}{S \cdot f_l + i(f_h - f_l)} \qquad i=1, 2, 3, \cdots, S \tag{2}$$
$$A_i = \frac{A_0}{S}$$

where

$$f_l = \frac{v}{L_l},\ f_h = \frac{v}{L_h} \qquad v: \text{SAW velocity}$$

(2) Equivalent circuit

In the i-th channel, considering as normal electrodes, Smith's equivalent circuit can be adapted to each channel by using the above equation (1) or (2). The admittance matrices of the transmitting and the receiving transducers in the i-th channel which are obtained by Smith's equivalent circuit, are denoted by (Y_{ti}) and (Y_{ri}) respectively. And the propagation characteristic impedance and the admittance matrix of the i-th channel are denoted by $Z_0 i$ and (Y_{li}), respectively. The block diagram for the i-th channel is shown Figure 3(a). By converting Figure 3(a) to the equivalent 4-terminal circuit like Figure 3(b), the admittance matrix (Y_i) can be obtained. Finally, by connecting the admittance matrices (Y_i)'s in



(a) Block diagram for i-th channel
(b) 2-port network equivalent to diagram (a)
(c) Parallel connection

Fig. 3. Equivalent circuit.

parallel as shown in Figure 3(c), then overall admittance matrix of the slanted finger transducer can be obtained.

(3) Finger pair weighting

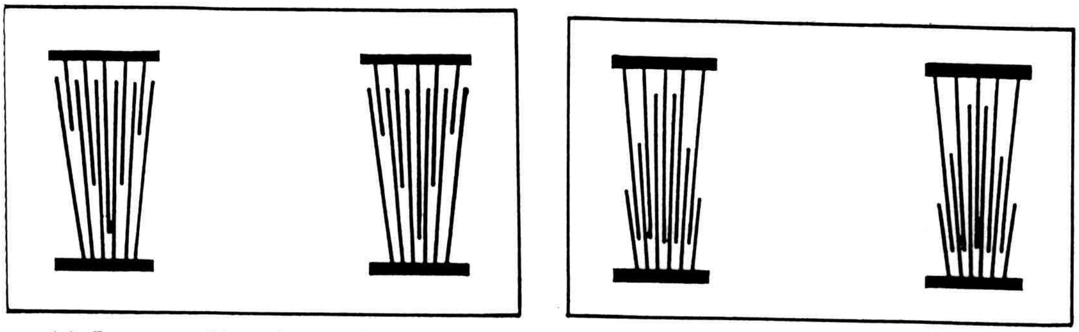
The slanted finger transducer can be approximated as parallel connection of multiple normal electrodes having different center frequencies. Frequency characteristic of the slanted finger transducers is a function of the input admittance of the transducer Y_{in}.

$$\begin{aligned} Y_{in} &= \sum_{i=1}^{S} (G_{ai} + jB_{ai}) + \sum_{i=1}^{S} j\omega C_u \cdot A_i \cdot N \\ &= Y_m + j\omega C_u \cdot N \cdot A_0 \end{aligned} \quad (3)$$

where G_{ai} : motional conductance of the i-th channel
B_{ai} : motional susceptance of the i-th channel
Y_m : motional admittance of the transducer
C_u : capacitance of a finger pair per unit length

As shown in Equation (3), input admittance Y_{in} depends on the motional conductance and the motional susceptance due to SAW radiation, and the susceptance due to electrode capacitance. In the slanted finger transducers, as tilt angle of the transducer becomes larger, the effect of the offaxis beam steering becomes not be negligible. Under the condition of a maximum finger tilt angle is constant, the total aperture length becomes larger with increase of the filter bandwidth. In the case of narrow-band filter, total aperture length is not so large, then, the effect of shunt capacitance is relatively small, and the motional conductance and the motional susceptance have dominant role. On the other hand, in the case of the wide-band filter, total aperture length becomes larger, and the shunt effect of the electrode capacitance becomes not be negligible. Shunt effect of the capacitance of the electrode results in decreasing high frequency component, that is right downward characteristic in pass-band response.

To correct these phenomena, three methods are used ; the first one is using the external circuit, the second one is changing the number of finger pairs of each channel, and the last one is changing the aperture length of each channel. Here we employ the second method. The



(a) For correction of upward incline. (b) For correction of downward incline.

Fig. 4. Finger pair weighting.

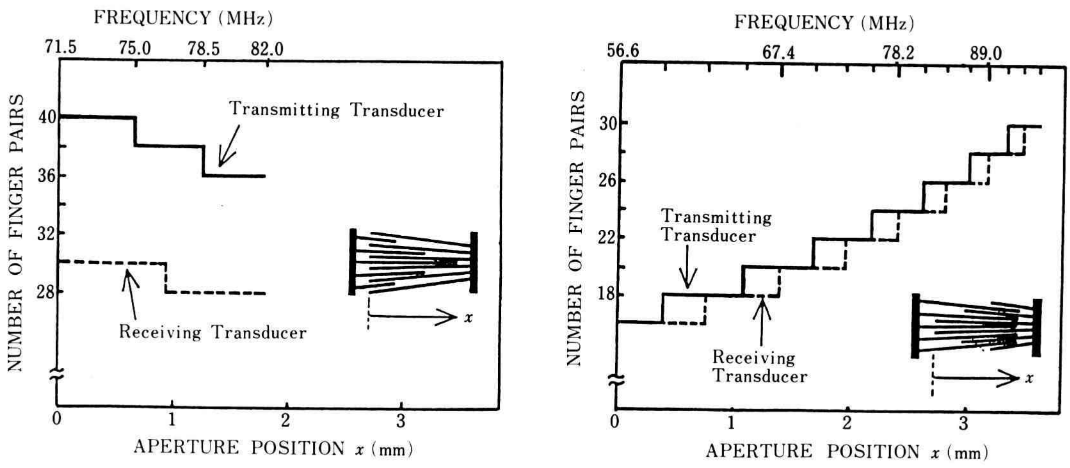
finger pair weighting method by changing the number of finger pairs of each channel corresponding to frequencies results in the flat pass-band characteristics as shown in Figure 4(a) and (b). Figure 4(a) is used for weighting for the right upward inclination, and (b) is used for weighting for the right downward inclination. To design this weighting, the function is determined so as to flat the pass-band after equivalent circuit calculation as changing the number of finger pairs of electrodes of each channel.

2.2 Experiments

Experiments on two filters with fractional bandwidth of 13% and 50% are made at the center frequency of 76.8 MHz. The two filters are fabricated on Y-Z $LiNbO_3$ substrates.

In each filter, the transmitting and receiving transducers are weighted by different functions. For weighting, the construction of Figure 4(a) is applied to the filter with 13% fractional bandwidth, and the construction of Figure 4(b) is applied to the filter with 50% fractional bandwidth. Details of the weighting functions are shown in Figure 5(a) and (b). Lower abscissa indicates the aperture position, and upper abscissa indicates the corresponding frequency. In these figures, the lower abscissa is indicated by linear scale, then the envelope of stepwise weighting function is not linear. If the upper abscissa is indicated by linear scale, the envelope of stepwise weighting function is linear. Figure 5(a) corresponds to the filter with 13% fractional bandwidth, and 5(b) corresponds to the filter with 50% fractional bandwidth respectively.

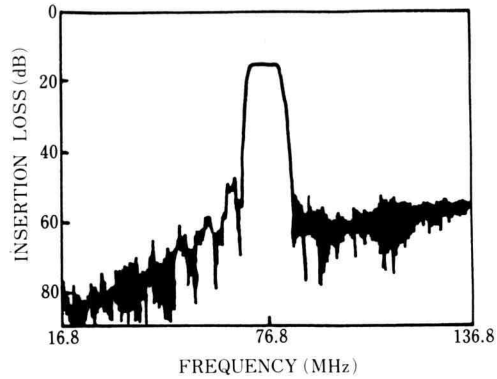
Figure 6(a) and (b) show the characteristics of the filter with 13% fractional bandwidth. The insertion loss is 14.4 dB and the ripple in the pass-band is within ± 0.3 dB. The stop band first side-lobe suppression of 32.5 dB was obtained by selecting 40 and 30 finger pairs of the transmitting and receiving transducers, respectively.



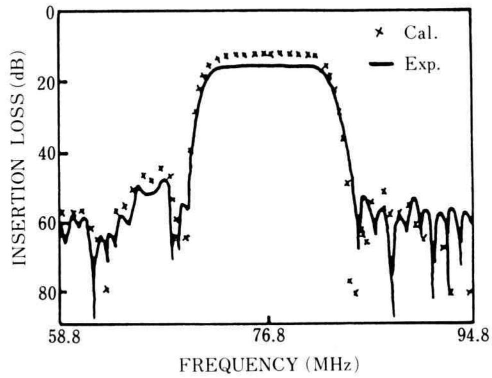
(a) For 13% fractional bandwidth filter.

(b) For 50% fractional bandwidth filter.

Fig. 5. Weighting functions of transducers.

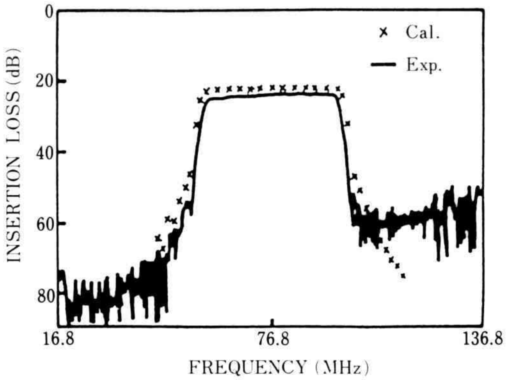


(a) Amplitude characteristic.

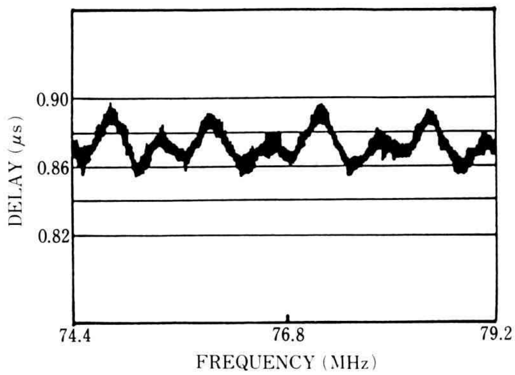


(b) Amplitude characteristic.

Fig. 6. 13% fractional bandwidth filter.



(a) Amplitude characteristic.



(b) Group delay characteristic.

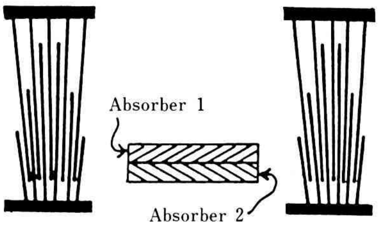
Fig. 7. 50% fractional bandwidth filter.

Figure 7(a) shows the frequency characteristic of the filter with 50% fractional bandwidth. The insertion loss is 23.3 dB and ripple due to feed-through in the pass-band is within ±0.2 dB. Deviation in the pass-band is within 1 dB. The first side-lobe suppression is about 27 dB. Good agreements are obtained between calculation and experiment. In the calculation, number of division of the transducer is 60 for 13% fractional bandwidth filter, and 90 for 50% fractional bandwidth filter respectively.

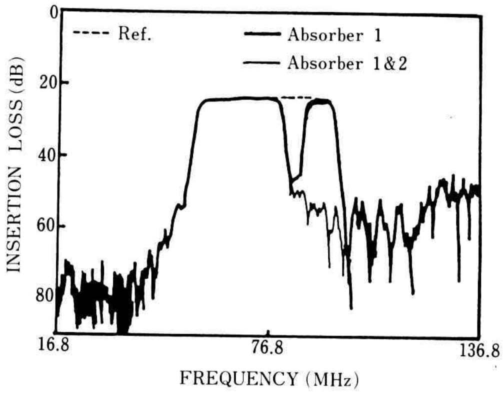
Figure 7(b) shows a group delay characteristic of the filter having 50% fractional bandwidth. The group delay variation in the pass band is within ±15 ns.

3. Controllability of pass-band characteristics

The pass-band characteristics of the filter composed of slanted finger transducers, can be designed by using the propagation path. In the slanted finger transducer devices, the propagation path for each frequency in the device bandwidth is distributed spatially. Thus,



(a) Absorber.



(b) Amplitude characteristic.

Fig. 8. Fixed notch filter.

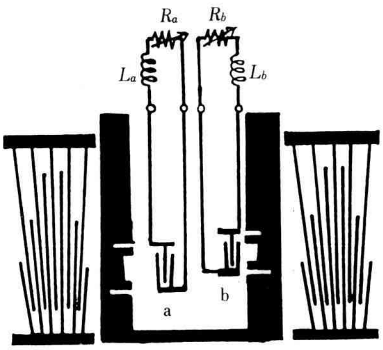
SAW can be attenuated in the propagation path of the channel corresponding to the desired frequency and the pass-band characteristics can be changed. There are many applications of the above methods. One is to obtain the notch characteristics by arranging absorbers on the propagation path, and the other is to obtain the variable notch characteristics by arranging subsidiary transducers for SAW reflection and using external circuit. The above mentioned filters with 50% fractional bandwidth were used in the experiments.

3.1 Fixed notch filters

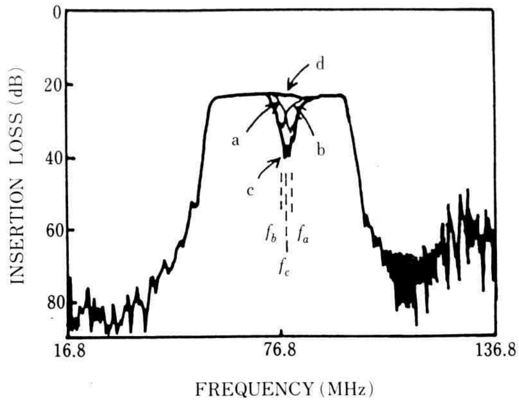
The absorber (silicon rubber) is arranged on the propagation path of the filter with 50% fractional bandwidth as shown in Figure 8(a). The frequency characteristic is same as Figure 7(a), when SAW absorber is not arranged. The thick solid line in Figure 8(b) shows the frequency characteristic in this case where SAW absorber "1" is arranged. In this case, SAW in the channel where absorber "1" arranged is attenuated by 20 dB. And the stop-band which is 3 MHz bandwidth corresponding the center frequencies of the channels is formed in the pass-band. Next, the thin solid line in Figure 8(b) shows the frequency characteristic in this case where SAW absorber "1" and "2" are arranged as shown Figure 8(a). In this case, SAW is also attenuated 20 dB or more. The pass-band characteristic formed by channels where SAW absorber not arranged is not affected. As for this device, spurious due to bulk wave appeared outside the bandwidth. This is because the rough finish is not made on the rear side of the device. From the above experiments, it can be said that any desired bandwidth in the pass-band can be stopped by arranging SAW absorber on the propagation path. This technique can be applied to filters whose pass-band characteristic is complicated, such as notch filters and multi-band filters.

3.2 Variable notch filter

On the propagation path of the filter with 50% fractional bandwidth, two subsidiary



(a) Subsidiary transducers.



(b) Amplitude characteristic.

Fig. 9. Variable notch filter.

transducers shown in Figure 9(a) are arranged and a coil and resistor are connected as an external circuit. There are the tuning coil to make the subsidiary transducer acts as SAW reflector, and the variable resistor to control the reflection characteristics. In this fabrication, one problem is that a large phase error can be caused by arranging the subsidiary transducers between the transmitting and receiving transducers, because the metal widths are different in adjacent channels. When the difference between the metal widths in adjacent channels is ΔL, the phase error $\Delta\phi$ is given by

$$\Delta\phi = 2\pi \cdot \Delta L\left(\frac{f}{v_m} - \frac{f}{v_0}\right) \tag{4}$$

where v_m is short circuit SAW velocity, v_0 is free SAW velocity. Since the electromechanical coupling coefficient k^2 is given by

$$k^2 = 2\frac{v_0 - v_m}{v_m} \tag{5}$$

the phase error is given as a function of k^2,

$$\Delta\phi = \frac{2\pi}{\lambda_0} \cdot \Delta L \cdot \frac{k^2}{2} \tag{6}$$

where

$$\lambda_0 = \frac{v_0}{f}$$

For example, when the difference between the metal widths in adjacent channels ΔL is $20\lambda_0$, and k^2 is 0.05, the phase error $\Delta\phi$ is π radian. Since the filter response is determined by overlapping of each channel response, the distortion can be appeared. In this experiment, to correct the phase error in each channel, the dummy grounded electrodes are placed as shown in Figure 9(a).

In the experiment, after frequency tuning process by L_a and L_b, effects of the variable resistors R_a and R_b on the pass-band frequency characteristics were observed.

When $R_a=\infty$ and $R_b=\infty$, both subsidiary transducers "a" and "b" are not acted as reflectors and the pass-band characteristic was flat and no notch effect is observed. This characteristic is shown as sign "d" in Figure 9(b).

When $R_a=0$ and $R_b=\infty$, only subsidiary transducer "a" was acted as a reflector and component of the frequency f_a corresponding to that channel was eliminated. This characteristic is shown as sign "a" in Figure 9(b).

When $R_a=\infty$ and $R_b=0$, only subsidiary transducer "b" is acted as a reflector and component of the frequency f_b corresponding to that channel is eliminated. This characteristic is shown as "b" in Figure 9(b).

When $R_a=0$ and $R_b=0$, both subsidiary transducers "a" and "b" were acted as reflectors and both components of f_a and f_b are eliminated. The subsidiary transducers "a" and "b" had overlapping channel and the frequency component f_c corresponding to that overlapping channel had larger amount of attenuation, compared with f_a and f_b components. This characteristic is shown as "c" in Figure 9(b).

In the above description, values of resistance R_a and R_b are assumed 0 or ∞. However these resistance values are changeable continuously, then the attenuation amounts are also adjustable continuously. From the above experiment, it is shown that the pass-band characteristics can be changed by the external circuit. It is considered that this application is very important as a filter whose pass-band characteristics can be controlled by the external circuit.

4. Conclusion

To calculate the characteristics of the slanted finger transducers, transducers are divided to multiple channels. Each transducer performance corresponding to the divided channel is approximated as normal fingers, and Smith's equivalent circuit is applied to each finger. By using different number of finger pairs and different weighting functions to the transmitting and receiving transducers, wide-band filters having flat-response, small pass-band ripple and high side-lobe suppression are designed. Calculated characteristics are verified by experiments on the filters with 13% and 50% fractional bandwidth.

It has been demonstrated that characteristics of the SAW filters composed of the slanted finger transducers can be controlled by changing the condition of the propagation path. By arranging SAW absorber on the propagation path, notch filters having a stop-band in the pass-band, and multi-band filters having many pass-band can be realized very easily. By arranging subsidiary transducers on the propagation path, variable notch filters can be realized. It is shown that the pass-band characteristics can be controlled by the external circuit.

In this paper, techniques of designing filters composed of slanted finger transducers are studied, and feasibility of the slanted finger transducers are shown.

An item left to future concerning the slanted finger transducers is increasing of the stop-band attenuation. For this purpose, a withdrawal weighting technique is supposed to be useful one. The other item will be extension of techniques using the propagation path.

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