SAW Filter Transmission Characteristics Design with Genetic Algorithm

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요 약

SAW(Surface Acoustic Wave) 필터는 탄성표면파를 응용한 신호처리기능소자로, 각종 통신기기의 고주파회로의 대역통과필터로 이용된다. 기본적인 구성은 압전체 기판의 표면에 전기신호와 표면파를 서로 교환하기 위한 입/출력 IDT(interdigital transducer) 한 쌍으로 이루어진다. 그 주파수 특성은 입/출력 IDT의 간격과 각각의 길이에 의해 결정되어지며, 대역통과 필터의 특성을 지닌다. 본 논문은 이런 SAW 필터의 수치설계방법론에 관한 것이다. 입력 IDT의 전극의 길이를 변수로 정하고, 중심 주파수, 통과대역의 폭과 정지대역의 감소치가 주어졌을 때 적응/최적화 알고리즘을 이용하여 필터를 설계한다. 설계하고자 하는 필터 특성과 임의의 시간에 만들어진 필터와의 오차를 목적함수로 정하고, 이 목적함수를 최소화하는 것으로 필터의 설계가 가능하게 된다. SAW 필터의 계산 모델로는 델타 함수 모델과 등가회로 모델을 사용하였으며, 최적화 알고리즘으로는 유전자 알고리즘을 사용하였다.

ABSTRACT

The SAW device is extensively used as a electro-mechanical band-pass filter in which a two-pairs of interdigital transducers are provided over the surface of the piezoelectric substrate. For the design requirement, the central frequency and the bandwidth of the passband, and the attenuation level of the stopband region are specified. The configuration is made so as to satisfy the specification given. The central frequency is mainly determined by the distance between the pair of the finger electrodes. The design is considered as an optimization problem with which the error norm, the distance between the desired characteristics and the calculated for a given model is to be minimized. The delta function model and the electrical equivalent circuit model are utilized to represent the SAW filter characteristics. Genetic algorithm is used for optimization in which apodization of the transducer fingers is chosen as a design variable.

Keyword

SAW Filter, Optimum Design, Apodization, Delta Function Model, Equivalent Circuit Model, Genetic Algorithm

Ⅰ. Introduction

Surface acoustic waves (SAW) are the elastic waves that propagate over the free surface of a solid material [1,2]. They were first reported by Lord Rayleigh in 1855 who made a mathematical discussion referring to a homogeneous isotropic elastic body. SAW devices are an electro-mechanical system making use of this phenomenon. The application is extensively

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practiced as filtering and signal processing devices, which are used for middle frequency filters in televisions, the filters and oscillators in mobile communication sets because of their small size and high performance capability.

In this paper, the optimization of the frequency characteristics in SAW filter design is discussed. A SAW filter basically consists of a pair of transducers, an input interdigital transducer (IDT) and an output IDT, provided on the surface of a piezoelectric substrate over which the waves propagate. A voltage source is connected to the input IDT and a load resistance to the output IDT. Thus, the electrical energy is converted into mechanical energy due to the piezoelectric effect with the input IDT and mechanical waves transport the energy over the substrate surface to the output IDT where the mechanical energy is again converted to the electrical energy. This mechanism forms an electrical filtering device between the pairs of electrical terminals. Fig. 1 shows a configuration of the SAW filter. There are many models possible to describe the SAW filters. For the analysis and design, two models, a delta function model and an equivalent circuit model are employed.

The IDTs play an important roll for the frequency characteristics of SAW filter. The apodization in the input IDT is chosen to be the optimization variable. The delta function model and the equivalent circuit model are considered for the calculation of frequency characteristics of SAW filters. Genetic algorithm (GA) is utilized for the optimization.

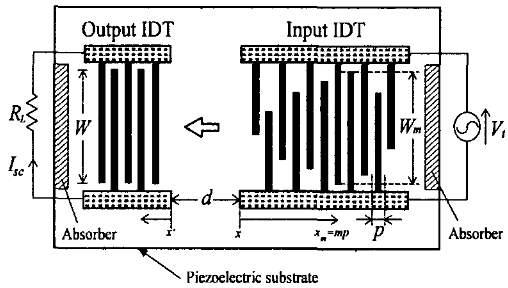
II. Delta Function Model

The delta function model [1,2,6] simply counts the time delay of the wave propagation. It is the simplest model to express the transmission characteristics of the filter, that provides a preliminary information for the transfer function or the filter response in bidirectional devices. It has the drawback which cannot include the effect of the velocity change due to the electrode mass loading and the electro-mechanical interactions, second-order effects like triple-transit echo (TTE) and the propagation loss.

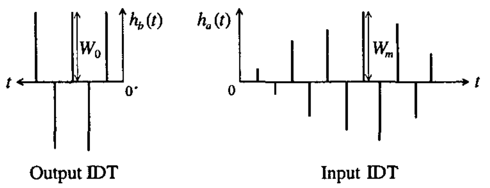
Fig. 1(a) shows the filter configuration. The output signal of the input IDT or the response $h_a(t)$ is given by [1,2]

$$h_a(t) = \sum_{m=1}^{M} W_m \delta(t - x_m/v) \tag{1}$$

at $x=0$, where W_m is a weighting figure corresponding to the finger overlap rate of the mth finger pair, $x_m = mp = m\lambda/2$ (m is integer), and $\lambda = v/f_0$. v is the surface wave velocity over the substrate and f_0 is the central frequency. It is represented by the impulse signals as shown in Fig. 1(b) on the right. Therefore, the frequency characteristics of the input IDT is given by the Fourier transform of the impulse train in Fig. 1(b) on the right, which is given as



(a)



(b)

Fig. 1 (a) A Bidirectional SAW Filter and (b) its Corresponding Delta Function Representation

$$H_a(\omega) = \sum_{m=1}^{M} W_m C_m \exp(-jkx_m) \quad (2)$$

where M is the number of fingers in input IDT. $k=\omega/v=2\pi f/v$, $C_m=(-1)^{m+1}$, and ω is angular frequency. The frequency characteristics of the output IDT is similar to Eq.(2) but with constant W_0 given by

$$H_b(\omega) = \sum_{n=1}^{N} W_0 C_n \exp(-jkx_n) \quad (3)$$

where W_0 is the finger overlap rate of the finger pairs, N is the number of input IDT, $x_n=np=n\lambda/2$ and $C_n=(-1)^{n+1}$ (n is integer).

A total frequency characteristics of a bidirectional SAW filter is thus given by

$$H(\omega)=H_a(\omega)\, H_b(\omega)\, \exp(-jkd) \quad (4)$$

where d is the distance between the input IDT and the output IDT.

III. Equivalent Circuit Model

The equivalent circuit model [1-3,6,7] is derived from the Mason's equivalent circuit originally employed for modelling acoustic bulk wave piezoelectric devices. Smith's 1st model as the equivalent circuit model is used in this paper, shown in Fig. 2, in which one periodic section of the IDT is modeled as a three-port network consisting of a pair acoustic ports with an electrical port, in which mechanical stress corresponds to the current. A three-port network expression is given from Fig. 2 as

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (5)$$

where

$$Y_{11} = Y_{22} = -jG_0 \cot\frac{\theta}{2}$$
$$Y_{12} = jG_0 \operatorname{cosec}\frac{\theta}{2}$$
$$Y_{13} = -Y_{23} = -jG_0 \tan\frac{\theta}{4}$$
$$Y_{33} = j\omega\frac{C_s}{2} + j2G_0\tan\frac{\theta}{4}$$
$$Y_{ji} = Y_{ij}$$
$$\theta = \frac{\omega l}{v_0} = 2\pi\frac{f}{f_0}$$

Y_{ij} of the transducer electrodes are given by the N cascade connection of the three-port network.

The F parameter of the SAW filter is derived for the frequency characteristics evaluation, which is defined as shown in Fig. 3. It is a cascade connection of F parameter of the input IDT, the propagation line and the output IDT as shown in Fig. 4.

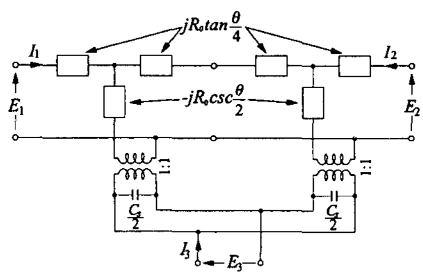


Fig. 2 Smith's 1st Model

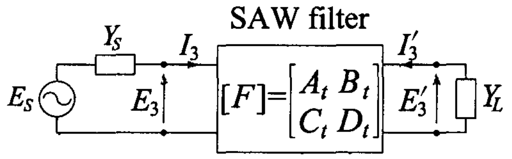


Fig. 3 F Parameter Representation of a SAW Filter

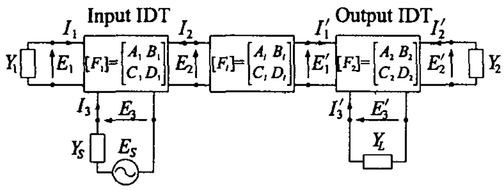


Fig. 4 F Parameter Representation of Each Section

As the F parameter of each section is known, the total F parameter of the SAW filter is determined to have the expression

$$\begin{bmatrix} E_3 \\ I_3 \end{bmatrix} = \begin{bmatrix} A_t & B_t \\ C_t & D_t \end{bmatrix} \begin{bmatrix} E'_3 \\ -I'_3 \end{bmatrix} \tag{6}$$

The frequency characteristics of the SAW filter is thus obtained to give

$$\begin{aligned} H(\omega) &= \frac{E'_3}{E_3} \\ &= \left(A_t + B_t Y_L + \frac{C_t}{Y_G} + \frac{D_t Y_L}{Y_G} \right)^{-1} \end{aligned} \tag{7}$$

Ⅳ. Optimization and Genetic Algorithm

The objective function for the frequency characteristics optimization is defined as

$$\varepsilon = \frac{1}{L} \sum_{j=1}^{L} | D(\omega_j) - H(\omega_j) |^2 \tag{8}$$

where $D(\omega_j)$ is the desired characteristics on the frequency point j that is given, $H(\omega_j)$ is the calculated characteristics on the same frequency point. L is the number of evaluation points in the frequency which is chosen to be 128.

The GA is a search algorithm based on the mechanism of natural genetics and natural selection. It helps not to take the local optimum but to converge to the global optimum [3-5,8].

The progress of the iterative calculation made through the following steps :

1. It first generates an initial population using random function. Each chromosome are structured binary $16 \times N$ bit, where N is chosen to be 8 (See Fig. 5). It is transformed to the real variable as

$$X = X_{\min} + \frac{(X_{\max} - X_{\min})K}{2^N - 1}$$

   where $X_{\min} \le X \le X_{\max}$ and K is a decimal number.

2. The error is calculated between the desired characteristics and the frequency characteristics evaluated each generation.

3. Then, the next-generation-population is determined out of the existing population.
4. The reproduced individuals are crossed by using the cross-over-operator.
5. The separate bits are swapped by the mutation operator. The next-generation- population is thus made out.

The progress from step 2 to step 5 is iteratively repeated until 20000th generations, in which population is chosen to be 30, crossover rate be 0.3, mutation rate be 0.02, and one-point crossover is used.

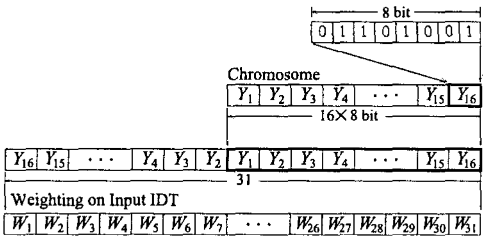


Fig. 5 Relation between Chromosome's Structure and Input IDT's Electrodes

V. Numerical Demonstration for Filter Design

The width of electrodes or the distance between each electrode pair, and the length of each electrode can be design parameters in a SAW filter. Here is only concerned with the length variation of the electrodes (Apodization) in the input IDT for the optimization of the frequency characteristics.

In the filter design, specification will be given for the bandwidth of the passband, the ripple in the passband and the level of the attenuation over the stopband. If the following two conditions are all qualified, a SAW filter is considered to be properly designed.

1. The bandwidth ($\Delta f = f_1 \sim f_2$ =-3dB point frequencies in the passband) and the ripple in the passband must be below an assigned value respectively.
2. The attenuation over the stopband must be below an assigned value.

For all the calculation to follow, it is assumed that input IDT consists of 15 and a half pairs(31 fingers) and the output IDT consists of 5 pairs(10 fingers).

The specification is that

1. The bandwidth of the passband is 12.5% ($= \Delta f / f_0 \times 100\%$, for the central frequency). The ripple in the passband is within -3dB.
2. The attenuation over the stopband must be below an assigned value.
3. The siderobe level over the stopband is below -40dB.

For the demonstration, the realistic concrete parameters are chosen as follows. The central frequency $f_0 = 4$MHz or $\lambda_0 = 872\mu m$. The material of the substrate is YZ-lithium niobate in which the surface acoustic velocity $v = 3488\,m/s$. The electrode length of the output IDT $W_0 = 100\lambda_0$. The electro-mechanical coupling coefficient $K^2 = 4.6\%$. The capacitance/finger pair/m is $C_0 = 460\,pF/m$. $\alpha_0 = 0.0$ and $d = 20\lambda_0$ are taken in Eq.(5). $C_s = C_0 W_0$, $Y_1 = 8K^2 f_0 C_s N_1^2$, $Y_2 = 8K^2 f_0 C_s N_2^2$, where N_1 and N_2 are the number of the input IDT and that of the output IDT finger pairs. $Y_s = 1/50[℧]$ and $Y_L = 1/50[℧]$.

5.1 Delta Function Model

The frequency characteristics of input IDT only is first considered. The frequency characteristics achieved is shown in Fig. 6. The circles in the figure indicate -3dB points and corresponding frequencies in the passband and the horizontal line indicates a -40dB line, the attenuation required over the stopband. The fine line, the dotted line, and the bold line represent the results at iteration k = 200, 1500, and 20000. The weighting or the length of each electrode is shown in Fig. 7. The progress of the mean square error calculated by Eq.(8) is shown in Fig. 8. There is no change in the mean square error after about 7500th iterations. The desired frequency characteristics is achieved at about 7500th iteration. The distribution of each individual in the genetic algorithm are shown in Fig. 9. From the top, it corresponds the 1st, 6th, 11th and 16th finger of the input IDT. The individual has reached an optimum value, 0.00392, 0.0598, 0.53726 and 1 with the progress of the generation.

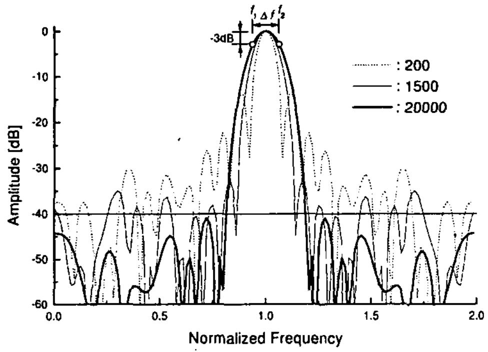


Fig. 6 Frequency Characteristics of Input IDT only [Delta Function Model]

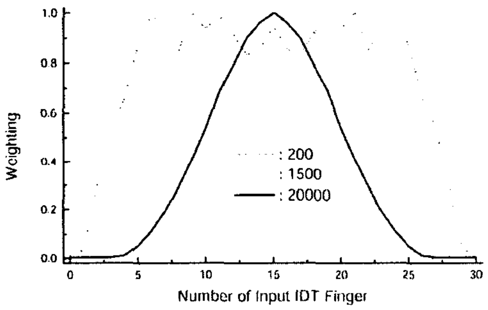


Fig. 7 Weighting on the Input IDT in Fig. 6

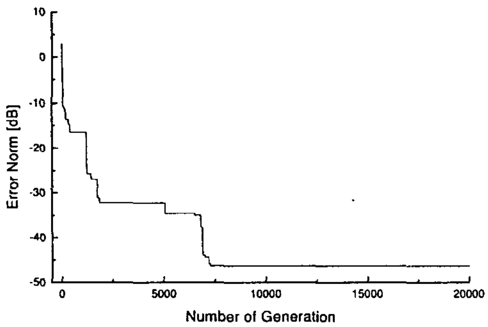


Fig. 8 Mean Square Error in Fig. 6

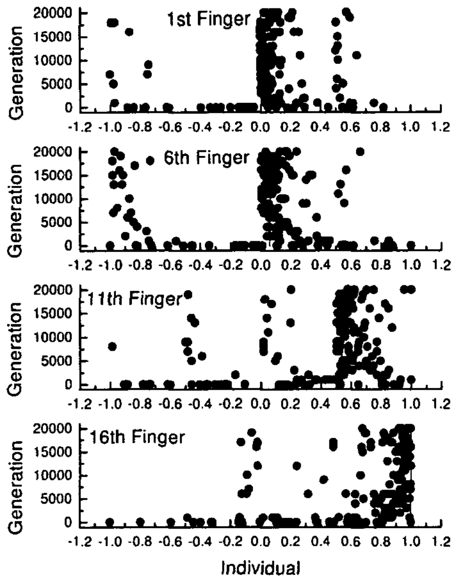


Fig. 9 The Distribution of Each Individual in Fig. 6

Secondly, the total frequency characteristics of SAW filter is calculated including the characteristics of the output IDT. The frequency characteristics can be evaluated by Eq.(3). The total frequency characteristics and the weighting of each electrode in the input IDT are shown in Fig. 10 and Fig. 11 respectively. The circles and the horizontal line indicate the same as before. The progress of the mean square error is shown in Fig. 12. It has cleared the desired frequency characteristics.

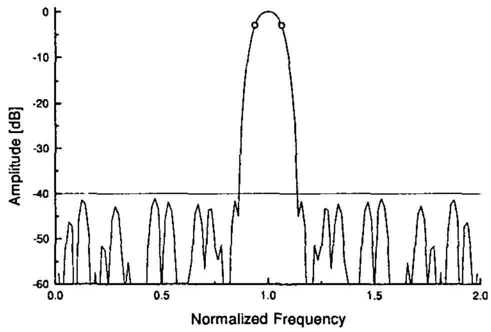


Fig. 10 Frequency Characteristics of the SAW filter [Delta Function Model]

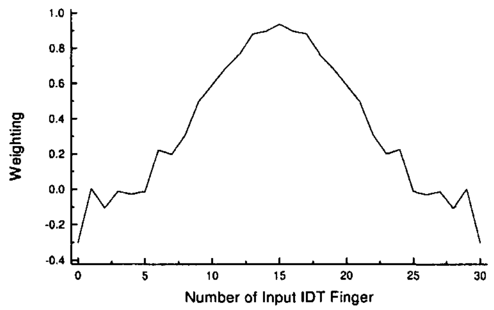


Fig. 11 Weighting on the Input IDT in Fig. 10

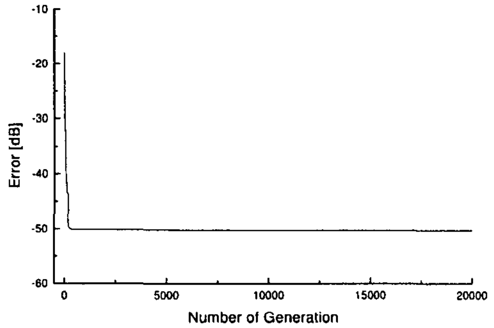


Fig. 12 Mean Square Error in Fig. 10

The execution time is about 60 seconds until 20000th iteration. The computer used for the simulation is a PC with DEC ALPHA 21164 Chip (533 MHz). The language is Fortran 77. The compiler is DIGITAL Fortran.

5.2 Equivalent Circuit Model

The frequency characteristics and the weighting of each electrode in the input IDT are shown in Fig. 13 and Fig. 14. The progress of the mean square error is shown in Fig. 15. There is no change in the mean square error after about 2500th iterations. The desired frequency characteristics is reached at about 2500th iteration. The time signal by inverse Fourier transform of Fig. 13 is shown in Fig. 16. The triple transit echo appears perhaps due to the reflection between input IDT and output IDT.

The execution time is as much as 3 hours until 20000th iteration. The apodized results achieved are similar to that of the delta function model. However, it is sometimes experienced that initial seed of the finger lead fluctuation. The relief for this symptom is to modify the initial seed slightly.

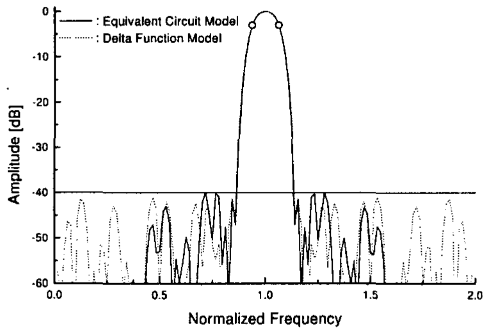


Fig. 13 Frequency Characteristics of the SAW filter [Equivalent Circuit Model]

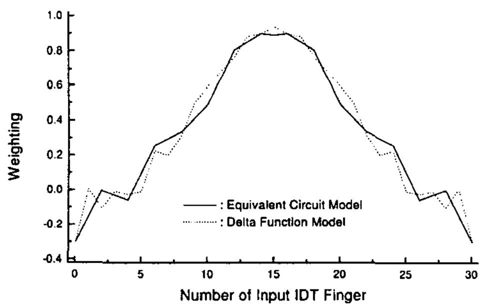


Fig. 14 Weighting on the Input IDT in Fig. 13

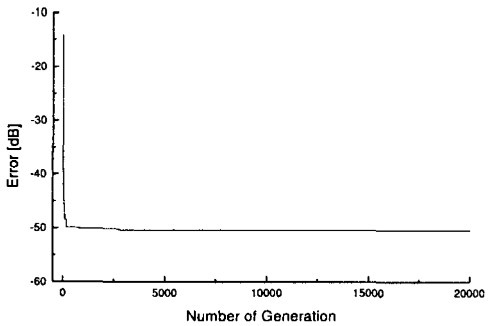


Fig. 15 Mean Square Error in Fig. 13

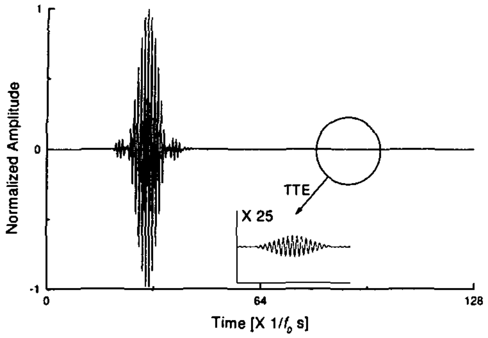


Fig. 16 A Time Signal corresponding to the Frequency Characteristics in Fig. 13

Ⅵ. Conclusions

The present paper demonstrated a design methodology of the SAW filters. The SAW filter expressed by the delta function model and the equivalent circuit model and their characteristics were considered for the optimization using genetic algorithm to meet the specification given. Apodization is chosen to be a design variable. Both modellings bring the similar result, though the latter modelling requires much longer execution time. The latter model will be preferable as it can include the effects of the insertion loss, the effect of the electro-mechanical coupling and the second-effects like the triple transit echo.

Acknowledgements

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