Simulation Modeling and Optimization Technique For Balanced Surface Acoustic Wave Filters

KIYOHARU TAGAWA
Department of Informatics
School of Science and Technology
Kinki University
3-4-1 Kowakae, Higashi-Osaka, 577-8502
JAPAN

Abstract: An optimum design technique for balanced surface acoustic wave (SAW) filters is proposed. First of all, in order to evaluate the performance of balanced SAW filters by the computer simulation, a numerical model of balanced SAW filters is derived by using mixed-mode scattering parameters. Then the structural design of balanced SAW filters is formulated as a function optimization problem that aims to improve their balance characteristics and satisfy specifications for filter characteristics. Furthermore, in order to solve the function optimization problem successfully, a simple and efficient global optimization method, i.e., the differential evolution (DE), is employed.

Key–Words: Surface acoustic wave filter, Optimum design, Differential evolution

1 Introduction

Recently, Surface Acoustic Wave (SAW) filters have played important roles as key devices for various mobile and wireless communication systems, such as Personal Digital Assistants (PDAs) and cellular phones[1, 2]. Especially, balanced SAW filters are used widely in the modern RF (Radio Frequency) circuits of cellular phones. Balanced SAW filters provide not only the band-pass filtering function but also some external functions such as unbalance-balance conversion and impedance conversion. Therefore, by using balanced SAW filters, conventional balun coils and matching devices can be omitted. As a result, the whole RF circuit design is simplified[2].

The frequency response characteristics of SAW filters are governed primarily by their geometrical structures, namely, the configurations of Inter-Digital Transducers (IDTs) and Shorted Metal Strip Array (SMSA) reflectors fabricated on piezoelectric substrates. Therefore, in order to realize desirable filter characteristics by SAW filters, several optimum design techniques coupling optimization methods with computer simulations are employed to decide their suitable structures[3, 4, 5, 6]. However, conventional optimum design techniques for SAW filters can't be applied directly to the structural design of balanced SAW filters. That is because not only the filter characteristics but also the balance characteristics of balanced SAW filters have to be considered in their structural design based on the computer simulation.

In this paper, an optimum design technique for balanced SAW filters is proposed. First of all, in order to evaluate the performance of balanced SAW filters by the computer simulation, a numerical model of them is derived by using mixed-mode scattering parameters (s-parameters)[7]. Then the structural design of balanced SAW filters is formulated as a function optimization problem that aims to improve both the balance characteristics and the band-pass filter characteristics. Incidentally, traditional equivalent circuit modes of SAW filters have been also used in the design of balanced SAW filters[8]. However, equivalent circuit modes become too complex to simulate the whole behaviors of balanced SAW filters.

For solving the above function optimization problem successfully, differential evolution (DE) is employed. DE is a global optimization method belonging to evolutionary computation[9]. Since DE is more simple and efficient in comparison with Genetic Algorithm (GA), it is often applied to practical large-sized optimization problem[10]. In this paper, a basic DE (DE/rand/1/bin)[9] is chosen from several DE versions because of it simplicity. However, in order to enhance the search ability of the basic DE, a distorted problem space of the structural design of balanced SAW filters is embedded dexterously in a regularized continuous search space. Finally, through the computational experiments conducted on a practical balanced SAW filter, the usefulness of the proposed optimum design technique is demonstrated.

2 Balanced SAW Filter

2.1 Basic Structure and Principle

Figure 1 shows a typical structure of the balanced SAW filter, which consists of five components: one transmitter IDT (IDT-T), two receiver IDTs (IDT-R) and two grating reflectors realized by SMSAs. Each of IDTs is composed of some pairs of electrodes called fingers and used for SAW excitation and detection. Even though the balanced SAW filter is a kind of resonator-type SAW filter that has a symmetrical structure[6], the polarities of the two receiver IDTs' electrodes are designed to be opposite. Therefore, a pair of port-2 and port-3 in Fig. 1 provides a balanced output-port for operating a differential mode signal, while the port-1 connected to the transmitter IDT is an unbalanced input-port of a single mode signal.

2.2 Modeling and Simulation

In order to analyze the frequency response characteristics of balanced SAW filters based on the computer simulation, a numerical model of them is derived. First of all, the behavior of each IDT with N-pair of fingers can be analyzed by using a three-port circuit illustrated in Fig. 2: port-a and port-b are acoustic ports, while port-c is an electric port[11]. Circuit elements included in Fig. 2 are given as follows.

$$\left[\begin{array}{lcl} A_{10} &=& \tanh\left(\frac{\gamma_s}{2}\right)\tanh(N\gamma_s) \\ A_{20} &=& \mp A_{10} \\ Z_1 &=& \frac{1}{R_0\,F_s}\tanh(N\gamma_s) \\ Z_2 &=& \frac{1}{R_0\,F_s}\operatorname{cosech}(2N\gamma_s) \\ Y_m &=& \frac{2\,F_s}{R_0}\tanh\left(\frac{\gamma_s}{2}\right) \\ && \left[2N-\tanh\left(\frac{\gamma_s}{2}\right)\tanh(N\gamma_s)\right] \\ C_T &=& N\,C_{so}\frac{K\left(\sin\left(\eta\frac{\pi}{2}\right)\right)}{K\left(\cos\left(\eta\frac{\pi}{2}\right)\right)} \end{array}\right. \tag{1}$$

where, the dual sign ($\mp$) means that the minus ($-$) is for $2N$ being an even number, while the plus ($+$) is for $2N$ being an odd number. R_0 denotes characteristic impedance. F_s is image admittance and γ_s is image transfer constant. $K(u)$ is the complete elliptic integral of the first kind of a real number $u \in \mathbb{R}$.

Furthermore, shorting the electric port (port-c) of the equivalent circuit model of IDT in Fig. 2, the equivalent circuit model of SMSA reflector is obtained[11]. Since the components of a SAW filter are connected acoustically in cascade on a piezoelectric substrate, the equivalent circuit model of the SAW filter can be composed from their components' circuit models. For example, the equivalent circuit model of the balanced SAW filter shown in Fig. 1 is represented by a six-port circuit in Fig. 3: a pair of port-2 and port-3 corresponds to the balanced output-port, while port-1 is the unbalanced input-port. Also, C_h and C_g denote coupling capacitances between one transmitter IDT and two receiver IDTs. The difference of the two values of C_h and C_g ($C_h > C_g$) deteriorates the balance characteristics of the balanced SAW filter.

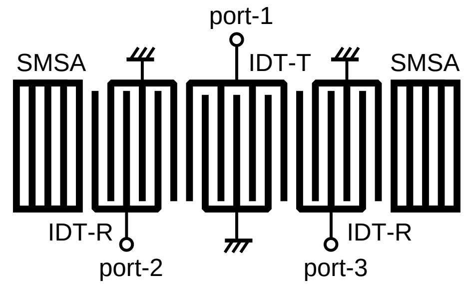

Figure 1: Balanced SAW filter

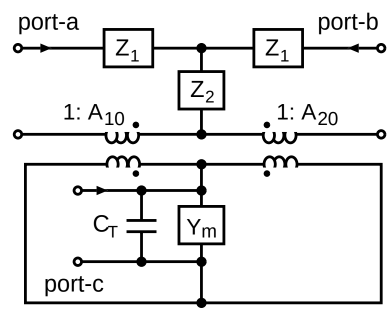

Figure 2: Equivalent circuit model of IDT

Terminating extra ports of the circuit model in Fig. 3, the balanced SAW filter shown in Fig. 1 is represented by an admittance matrix Y as follows.

$$Y = \begin{bmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{32} & y_{33} \end{bmatrix} \tag{2}$$

Furthermore, considering the impedances of the input-port Z_{in} and the output-port Z_{out}, the admittance matrix Y in (2) can be transformed into a so-called scattering matrix S as follows[12].

$$S = B\,A^{-1} = \begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix} \tag{3}$$

where, matrixes A and B are given as follows.

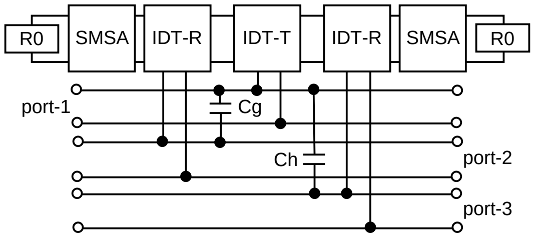

Figure 3: Circuit model of balanced SAW filter

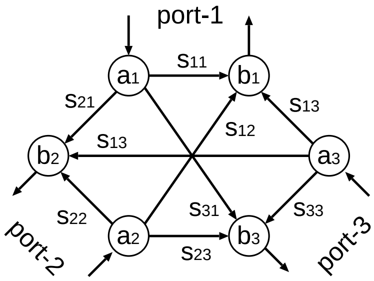

Figure 4: Network model of balanced SAW filter

$$A = \begin{bmatrix} 1 + Z_{in}\, y_{11} & Z_{in}\, y_{12} & Z_{in}\, y_{13} \\ -Z_{out}\, y_{21} & 1 + Z_{out}\, y_{22} & -Z_{out}\, y_{23} \\ -Z_{out}\, y_{31} & -Z_{out}\, y_{32} & 1 + Z_{out}\, y_{33} \end{bmatrix}$$

$$B = \begin{bmatrix} 1 - Z_{in}\, y_{11} & -Z_{in}\, y_{12} & -Z_{in}\, y_{13} \\ Z_{out}\, y_{21} & 1 + Z_{out}\, y_{22} & Z_{out}\, y_{23} \\ Z_{out}\, y_{31} & Z_{out}\, y_{32} & 1 + Z_{out}\, y_{33} \end{bmatrix}$$

From the scattering matrix S in (3), a three-port network model of the balanced SAW filter is derived as shown in Fig. 4: a pair of port-2 and port-3 corresponds to the balanced output-port, while port-1 is the unbalanced input-port. Signals entering the SAW filter from the outside enter at a_k $(k = 1,\ 2,\ 3)$ nodes and signals leave the network through b_k nodes. The three-port network model in Fig. 4 can be also used to graphically visualize the signal flow between ports of the balanced SAW filter and simplify its analysis.

2.3 Balance Characteristics

In order to evaluate the balance characteristics of balanced SAW filters, two criteria are used. It is desirable that the output signals from the balancing ports, namely port-2 and port-3 in Fig. 4, have the same amplitude and 180 degrees phase difference. Therefore, the amplitude balance of balanced SAW filters is evaluated by criterion Γ_1 in (4), and the phase balance is also evaluated by criterion Γ_2 in (5). As previously said, in an ideal balanced SAW filter, both of criteria Γ_1 and Γ_2 are equal to zero through the pass-band.

$$\Gamma_1 = 20\ \log_{10}(|s_{21}|) - 20\ \log_{10}(|s_{31}|) \qquad (4)$$

$$\Gamma_2 = \varphi(s_{21}) - \varphi(s_{31}) + 180 \qquad (5)$$

where, $\varphi(s_{ij})$ denotes the phase angle of s_{ij}.

2.4 Filter Characteristics

In order to evaluate the frequency response characteristics of balanced SAW filters strictly, differential mode signals and common mode signals need to be segregated in the three-port network model in Fig. 4. According to the theory of balanced network[7], the entering signals a_k $(k = 2,\ 3)$ and leaving signals b_k of the balanced output-port are reorganized into two mode signals: differential mode signals (a_d and b_d) in (6) and common mode signals (a_c and b_c) in (7).

$$\begin{cases} a_d = \dfrac{1}{\sqrt{2}}(a_2 - a_3) \\ b_d = \dfrac{1}{\sqrt{2}}(b_2 - b_3) \end{cases} \qquad (6)$$

$$\begin{cases} a_c = \dfrac{1}{\sqrt{2}}(a_2 + a_3) \\ b_c = \dfrac{1}{\sqrt{2}}(b_2 + b_3) \end{cases} \qquad (7)$$

From (6) and (7), conventional s-parameters in (3) are converted into the mix-mode s-parameters as follows, where s_{11} and s_{dd} are referred as reflection coefficients, and s_{d1} is transmission coefficient[7].

$$S_{mix} = T\,S\,T^{-1} = \begin{bmatrix} s_{11} & s_{1d} & s_{1c} \\ s_{d1} & s_{dd} & s_{dc} \\ s_{c1} & s_{cd} & s_{cc} \end{bmatrix} \qquad (8)$$

where, matrix T is given as follows.

$$T = \frac{1}{\sqrt{2}} \begin{bmatrix} \sqrt{2} & 0 & 0 \\ 0 & 1 & -1 \\ 0 & 1 & 1 \end{bmatrix}$$

In order to evaluate the frequency response characteristics of SAW filters, three criteria are used. From the above reflection coefficients in (8), standing wave ratios Γ_3 and Γ_4 are defined for the input- and output-ports of balanced SAW filters as follows.

$$\Gamma_3 = \frac{1 + |s_{11}|}{1 - |s_{11}|} \qquad (9)$$

$$\Gamma_4 = \frac{1 + |s_{dd}|}{1 - |s_{dd}|} \qquad (10)$$

Besides them, from the transmission coefficient in (8), attenuation Γ_5 is also defined as follows.

$$\Gamma_5 = -20\ \log_{10}(|s_{d1}|) \qquad (11)$$

3 Problem Formulation

The structural design of balanced SAW filters is formulated as an optimization problem. First of all, we define the decision variables of the optimization problem. The frequency response characteristics of SAW filters depend on their structures, or the configurations of components fabricated on piezoelectric substrates. Therefore, as well as conventional optimum design techniques for SAW filters, design parameters describing the structure of a balanced SAW filter are selected as decision variables: $\boldsymbol{x} = (x_1, \cdots, x_D)$. For example, the numbers of IDTs' fingers, the number of SMSAs' strips, and the overlap between electrodes are included in decision variables. Also, the values of respective decision variables $x_j \in \boldsymbol{x}$ are bounded by their parametric limitations as follows.

$$\underline{x}_j \le x_j \le \overline{x}_j, \quad j = 0, \cdots, D-1. \tag{12}$$

Secondly, we define the objective function of the optimization problem. Let Ω_p be a set of frequency points sampled from the pass-band of the balanced SAW filter. Also let Ω_s be a set of frequency points sampled from the stop-band. The desirable filter characteristics of the balanced SAW filter is specified by the upper $U_r(\omega)$ $(r = 3, 4, 5)$ and the lower $L_r(\omega)$ bounds of the criteria $\Gamma_r(\omega, \boldsymbol{x})$ at $\omega \in \Omega_p \cup \Omega_s$, where the values of criteria depend on both the frequency ω and the decision variables $\boldsymbol{x}$. Therefore, considering all criteria Γ_r $(r = 1, \cdots, 5)$ for the SAW filter, the objective function $f(\boldsymbol{x})$ is defined as follows.

$$f(\boldsymbol{x}) = \sum_{r=1}^{5} \frac{\alpha_r}{|\Omega_p|} f_r(\boldsymbol{x}) + \frac{\alpha_6}{|\Omega_s|} f_6(\boldsymbol{x}) \tag{13}$$

where, α_r $(\alpha_r > 0)$ denote weighting coefficients.

$$\left[\begin{array}{l}
f_1(\boldsymbol{x}) = \sum_{\omega\in\Omega_p} \Gamma_1(\omega, \boldsymbol{x})^2 \\
f_2(\boldsymbol{x}) = \sum_{\omega\in\Omega_p} \Gamma_2(\omega, \boldsymbol{x})^2 \\
f_3(\boldsymbol{x}) = \sum_{\omega\in\Omega_p} \max\{\Gamma_3(\omega, \boldsymbol{x}) - U_3(\omega), 0\} \\
f_4(\boldsymbol{x}) = \sum_{\omega\in\Omega_p} \max\{\Gamma_4(\omega, \boldsymbol{x}) - U_4(\omega), 0\} \\
f_5(\boldsymbol{x}) = \sum_{\omega\in\Omega_p} \max\{L_5(\omega) - \Gamma_5(\omega, \boldsymbol{x}), 0\} \\
f_6(\boldsymbol{x}) = \sum_{\omega\in\Omega_s} \max\{\Gamma_5(\omega, \boldsymbol{x}) - U_5(\omega), 0\}
\end{array}\right.$$

From (12) and (13), the structural design of balanced SAW filters can be formulated precisely as a function optimization problem as follows.

$$\left[\begin{array}{ll}
\text{minimize} & f(\boldsymbol{x}) \\
\text{sub. to} & \boldsymbol{x} = (x_0, \cdots, x_{D-1}) \in \mathcal{X}
\end{array}\right. \tag{14}$$

where, $\mathcal{X}$ denotes a set of feasible solutions, or the problem space, satisfying the conditions in (12).

4 Differential Evolution

Differential Evolution (DE) is an efficient global optimization method applicable to non-differential, nonlinear and multimodal function optimization problems[9]. Therefore, in order to solve the optimization problem in (14), a basic DE is employed.

Since DE is an evolutionary computation, it executes a parallel direct search which utilizes NP D-dimensional parameter vectors $\boldsymbol{v}_G^i$ $(i = 1, \cdots, \mathrm{NP})$ as a population for each generation G. The initial population is chosen randomly. Then DE generates a new parameter vector by adding the weighted difference between two vectors to a third vector in the current population. This operation is called "mutation". The mutated vector's parameters are then mixed with the parameters of another predetermined vector, or the target vector, to create the so-called trial vector. This parameter mixing operation is called "crossover". If the trial vector yields a lower objective function value than the target vector, the trial vector replaces the target vector in the following generation. This last operation is called "selection". Each vector in the population has to serve once as the target vector so that NP competitions take place in one generation. The procedure of DE is detailed in the literature[9].

In order to apply the above basic DE to the optimum design problem of balanced SAW filters in (14) effectively, the distorted problem space $\boldsymbol{x} \in \mathcal{X}$ is embedded in a regularized continuous search space for DE. Exactly, the decision variables $x_j \in \boldsymbol{x} \in \mathcal{X}$ are represented by the DE's parameters $v_j \in \boldsymbol{v}_G^i \in \mathbb{R}^D$. Furthermore, the respective parameters' values $v_j \in \boldsymbol{v}_G^i$ are restricted in the search space as follows.

$$0 \le v_j \le 1, \quad j = 0, \cdots, D-1. \tag{15}$$

Then each $v_j \in \boldsymbol{v}_G^i$ in (15) is converted into the decision variable $x_j \in \boldsymbol{x} \in \mathcal{X}$ of the optimization problem in (14) when the objective function value $f(\boldsymbol{x})$ of $\boldsymbol{x} \in \mathcal{X}$ is evaluated based on the vector $\boldsymbol{v}_G^i$. If the decision value $x_j \in \boldsymbol{x}$ has to take a real number, the corresponding $v_j \in \boldsymbol{v}_G^i$ is converted into $x_j \in \boldsymbol{x}$ as shown in (16). On the other hand, if $x_j \in \boldsymbol{x}$ has to take a discrete value with an interval e_j, $v_j \in \boldsymbol{v}_G^i$ is converted into $x_j \in \boldsymbol{x}$ as shown in (17).

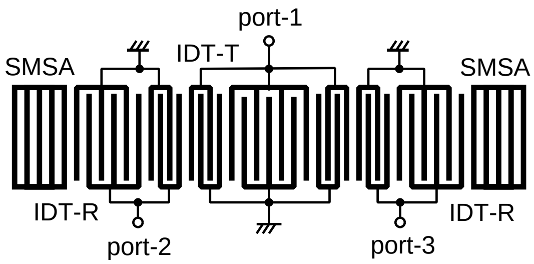

Figure 5: Practical balanced SAW filter

Table 1: Problem space

x_i	$[\underline{x}_i,\ \overline{x}_i]$	design parameter
x_0	[200, 400]	overlap of electrodes
x_1	[10.0, 20.0]	fingers' number of IDT-R
x_2	[15.5, 25.5]	ditto of IDT-T
x_3	[1.0, 3.0]	ditto of modulated IDT
x_4	[50, 150]	strips' number of SMSA
x_5	[0.4, 0.6]	metallization ratio of IDT
x_6	[0.4, 0.6]	ditto of SMSA
x_7	[0.91, 0.92]	pitch ratio of IDT
x_8	[1.00, 1.05]	ditto of SMSA
x_9	[1.95, 2.05]	finger pitch of IDT
x_{10}	[3900, 4000]	thickness of electrode

$$x_j = (\overline{x}_j - \underline{x}_j)\, v_j + \underline{x}_j \tag{16}$$

$$x_j = \mathrm{fix}\left(\frac{(\overline{x}_j - \underline{x}_j)}{e_j}\, v_j\right) e_i + \underline{x}_j \tag{17}$$

where, $\mathrm{fix}(u)$ converts a real number $u \in \mathbb{R}$ into an integer by omitting the lower than the decimal point.

5 Experimental Results

The optimum design technique using DE is applied to the structural design of a practical balanced SAW filter in Fig. 5, which consists of nine components including pitch-modulated IDTs[13]. Table 1 shows the problem space of the optimization problem, namely, the upper $\overline{x}_j$ and the lower $\underline{x}_j$ bounds of $D = 11$ design parameters $x_j \in \boldsymbol{x}$ $(j = 0, \ldots, D-1)$. The objective function $f(\boldsymbol{x})$ in (13) is evaluated with 401 frequency points. Also, the pass-band of the SAW filter is specified by the range: $950 \sim 980$ [MHz].

The basic DE was then applied to the optimum design problem 20 times with $\mathrm{NP} = 50$. Each run of DE spent about 20 minutes on a personal computer. Table 2 shows the experimental results averaged over 20 runs. In Table 2, the best objective function values $f(\boldsymbol{x}^\star)$ of the best solutions $\boldsymbol{x}^\star$ obtained at the initial ($G = 0$) and the final ($G = 100$) generations are described with their partial function values $f_r(\boldsymbol{x}^\star)$ $(r = 1, \cdots, 6)$ defined in (13). Besides the averages of function values $\hat{f}$, the standard deviations of them σ_f are also described in Table 2. From the results in Table 2, we can confirm that the final solutions are superior to the initial ones in all criteria Γ_r.

Table 2: Experimental results

$D = 11$	$G = 0$		$G = 100$	
	$\hat{f}$	σ_f	$\hat{f}$	σ_f
$f(\boldsymbol{x}^\star)$	3.357	0.3811	2.075	0.002
$f_1(\boldsymbol{x}^\star)$	177.6	45.79	72.77	1.019
$f_2(\boldsymbol{x}^\star)$	940.1	103.6	634.4	3.954
$f_3(\boldsymbol{x}^\star)$	38.74	11.51	26.07	1.479
$f_4(\boldsymbol{x}^\star)$	39.06	12.22	27.01	1.481
$f_5(\boldsymbol{x}^\star)$	9.147	4.030	5.907	0.530
$f_6(\boldsymbol{x}^\star)$	38.00	14.19	21.59	1.375

Observing the frequency response characteristics of the balanced SAW filter yielded by the best solution, we have verified the usefulness of the optimum design technique. For example, Fig. 6 shows the phase balance $\Gamma_2(\omega, \boldsymbol{x}^\star)$ defined in (5) for the best solution $\boldsymbol{x}^\star$ obtained by DE. From Fig. 6, we can confirm that the phase balance $\Gamma_2(\omega, \boldsymbol{x}^\star)$ holds nearly zero through the pass-band $\omega \in \Omega_p$. Also, Fig. 7 shows the attenuation $\Gamma_5(\omega, \boldsymbol{x}^\star)$ defined in (11) with the upper $U_5(\omega)$ and the lower $L_5(\omega)$ bounds of the criterion plotted by broken-line. From Fig. 7, we can confirm that the attenuation $\Gamma_5(\omega, \boldsymbol{x}^\star)$ meets the specifications for a desirable balanced SAW filter.

6 Conclusion

An optimum design technique for balanced SAW filters using DE was proposed. First of all, in order to evaluate the performance of balanced SAW filters based on the computer simulation, a numerical model of them was composed by using mixed-mode s-parameters. Then the structural design of balanced SAW filters was formulated as a function optimization problem for improving them in both the balance characteristics and the filter characteristics. For solving the optimization problem, a basic DE was employed. In this case, in order to enhance the search ability of the basic DE, the distorted problem space of the function optimization problem was embedded in a regu-

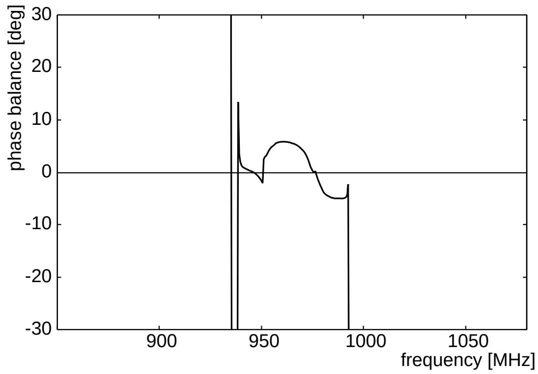

Figure 6: Phase balance characteristics

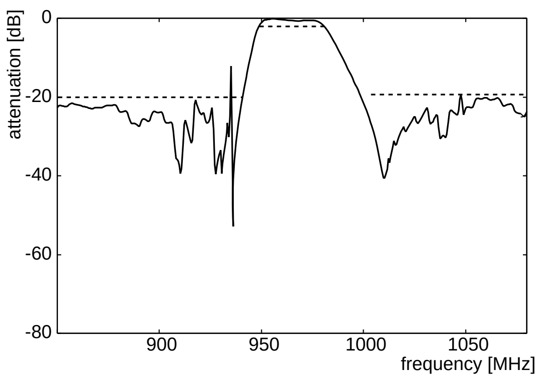

Figure 7: Filter characteristics (attenuation)

larized continuous search space. Finally, through the computational experiments conducted on a practical balanced SAW filter, the usefulness of the proposed optimum design technique was demonstrated.

Future work will focus on the revision of the basic strategy of DE used in this time. Since several variants of DE have been proposed[9], we would like to try them as well as other optimization methods[14].

Acknowledgements: The research was supported in part by the Grant-in-Aid for Scientific Research (C) (Project No. 18560402) from Japan Society for the Promotion of Science (JSPS).

References:

[1] C. K. Campbell, *Surface Acoustic Wave Devices for Mobile and Wireless Communication*, Academic Press, 1998.

[2] H. Meier, T. Baier and G. Riha, Miniaturization and advanced functionalities of SAW devices, *IEEE Trans. on Microwave Theory and Techniques*, 49–4, 2001, pp. 743–748.

[3] J. Franz, C. C. W. Ruppel, F. Seifert and R. Weigel, Hybrid optimization techniques for the design of SAW filters, *Proc. of IEEE Ultrasonics Symposium*, 1997, pp. 33–36.

[4] S. Goto and T. Kawakatsu, Optimization of the SAW filter design by immune algorithm, *Proc. of IEEE International Ultrasonics, Ferroelectrics, and Frequency Control Joint 50th Anniversary Conference*, 2004, pp. 600–603.

[5] J. Meltaus, P. Hämäläinen, M. M. Salomaa and V. P. Plessky, Genetic optimization algorithms in the design of coupled SAW filters, *Proc. of IEEE International Ultrasonics, Ferroelectrics, and Frequency Control Joint 50th Anniversary Conference*, 2004, pp. 1901–1904.

[6] K. Tagawa and H. Kim, A local search technique for large-scale optimum design problems of double mode SAW filters, *WSEAS Trans. on Circuits and Systems*, 1–6, 2007, pp. 1–8.

[7] D. E. Bockelman and W. R. Eisenstadt, Combined differential and common-node scattering parameters: theory and simulation, *IEEE Trans. on Microwave Theory and Techniques*, 43–7, 1995, pp. 1530–1539.

[8] M. Koshino, H. Kanasaki, T. Yamashita, S. Mitobe, M. Kawase, Y. Kuroda and Y. Ebata, Simulation modeling and correction method for balance performance of RF SAW filters, *Proc. of IEEE Ultrasonics Symposium*, 2002, pp. 301–305.

[9] R. Storn and K. Price, Differential evolution - a simple and efficient heuristic for global optimization over continuous spaces, *Journal of Global Optimization*, 11, 1997, pp. 341–359.

[10] K. V. Price, R. M. Storn and J. A. Lampinen, *Differential Evolution - A Practical Approach to Global Optimization*, Springer, 2005.

[11] T. Kojima and T. Suzuki, Fundamental equations of electro-acoustic conversion for an interdigital surface-acoustic-wave transducer by using force factors, *Japanese Journal of Applied Physics Supplement*, 31, 1992, pp. 194–197.

[12] K. Hashimoto, *Surface Acoustic Wave Devices in Telecommunications - Modeling and Simulation*, Springer, 2000.

[13] O. Kawachi, S. Mitobe, M. Tajima, T. Yamaji, S. Inoue and K. Hashimoto, A low-loss and wide-band DMS filter using pitch-modulated IDT and reflector structures, *Proc. of IEEE International Ultrasonics, Ferroelectrics, and Frequency Control Joint 50th Anniversary Conference*, 2004, pp. 298–301.

[14] S. M. Sait and H. Youssef, *Iterative Computer Algorithms with Applications in Engineering: Solving Combinatorial Optimization Problems*, Wiley-IEEE Computer Society Press, 2000.