Multi-Stage Design of DMS Filters with Free & Freeze Method

KIYOHARU TAGAWA
Faculty of Engineering
Kobe University
Rokkodai Nada Kobe 657-8501
JAPAN

HOEWON KIM
Graduate School of Science and Technology
Kobe University
Rokkodai Nada Kobe 657-8501
JAPAN

Abstract: The structural design of Double Mode Surface acoustic wave (DMS) filters, which are used widely for modern cellular phones, can be formulated as a combinatorial optimization problem. Even though the local search is usually efficient to solve the combinatorial optimization problem, the running time spent by the local search increases drastically when it is applied to a large-scale problem instance. Therefore, in order to solve the large-scale design problem of complex DMS filter in a short period, a new optimization technique named Free & Freeze method is proposed. Since Free & Freeze method is a kind of the divide-and-conquer method, it divides the search space of an optimization problem into two segments repeatedly, namely free-segment and freeze-segment, considering the problem landscape, and applies an efficient local search to the free-segment intensively.

Key–Words: Surface acoustic wave filter, Optimum design and Local search

1 Introduction

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]. Especially, Double Mode Surface acoustic wave (DMS) filters are used widely in their modern RF circuits, because they can provide small, rugged and cost-competitive mechanical bandpass filters with outstanding frequency response characteristics[2, 3].

The frequency response characteristics of SAW filters including DMS filters are governed primarily by their geometrical structures, namely, the configurations of interdigital transducers (IDTs) and grating reflectors fabricated on piezoelectric substrates. Therefore, in order to realize desirable frequency response characteristics of SAW filters, we have to decide their suitable structures. Because the structural design problems of SAW filters can't be solved theoretically, they are formulated as optimization problems. Then optimum design techniques coupling optimization methods with computer simulations are used to solve the optimization problems[4, 5, 6, 7, 8].

In recent years, cellular phones have become highly efficient with many functions. Since DMS filters are key devices for such modern cellular phones, the demand for high performance DMS filters meeting various specifications, such as high stop-band attenuation, low insertion loss, impedance transformation, balun functionality and so on, has increased. In order to satisfy these severe specifications, the structures of DMS filters have become extremely complex. Consequently, the numbers of design parameters used to describe DMS filters' structures, or the decision variables of optimization problems, have increased drastically. Besides, computational time spent to evaluate the performance of such a DMS filter based on computer simulation has also increased[9].

In this paper, to cope well with the large-scale design problems of DMS filters, a new optimization technique named Free & Freeze method is proposed. Since Free & Freeze method is a kind of the divide-and-conquer method, it divides the search space of an optimization problem into two segments repeatedly, namely free-segment and freeze-segment, and applies a local search to the free-segment intensively. As an efficient local search used in Free & Freeze method, Variable Neighborhood Search (VNS)[6] offered by authors is employed. That is because VNS has been applied successfully to various types of optimum design problems of SAW filters[6, 7, 8].

2 Double Mode SAW Filter

2.1 Structure of DMS Filter

Figure 1 shows a typical structure of double mode SAW (DMS) filter, which consists of five components: one receiver IDT (IDT-1), two transmitter IDTs (IDT-2) and two grating reflectors realized by shorted metal strip arrays (SMSA). Each of IDTs is composed of

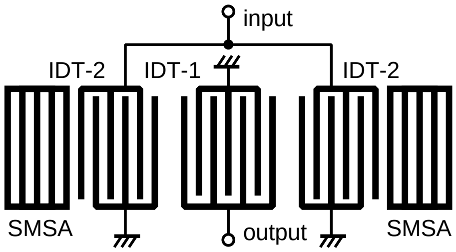
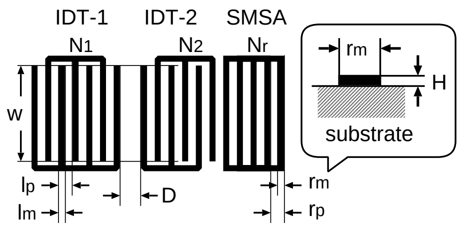


Figure 1: Double mode SAW filter



W : overlap between electrodes
N_1 : number of fingers of receiver IDT-1
N_2 : ditto of transmitter IDT-2
N_r : number of strips of SMSA
D : gap between IDT-1 and IDT-2
ξ : metallization ratio of IDT
ξ_r : ditto of SMSA
ρ_r : pitch ratio of SMSA to IDT
H : thickness of electrode

Figure 2: Design parameters of DMS filter

some pairs of electrodes called fingers and used for SAW excitation and detection. Since the DMS filter is designed to resonate at two different frequency-modes, it has a symmetric structure[2, 3].

The frequency response characteristics of DMS filters depend on their structures, or the configurations of components fabricated on piezoelectric substrates. For example, in order to decide a suitable structure of the DMS filter in Fig. 1, we need to adjust nine design parameters listed in Fig. 2. Since the DMS filter has a symmetric structure, Fig. 2 illustrates only its right half side. The metallization ratio of IDT is defined by the ratio of the finger's width l_m to the pitch of IDT's finger l_p as $\xi = l_m/l_p$. Similarly, the metallization ratio of SMSA is defined as $\xi_r = r_m/r_p$. The pitch ratio of SMSA to IDT is given by $\rho_r = r_p/l_p$.

From now on, the nine design parameters listed in Fig. 2 are referred as decision variables and represented by using a vector of $n = 9$ elements: $\mathbf{x} = (x_1, \cdots, x_n)$. By the way, some design parameters, such as the numbers of IDTs' fingers, take the values of positive integers. Besides, the lithographic resolution for shaping IDTs' electrodes is also restricted

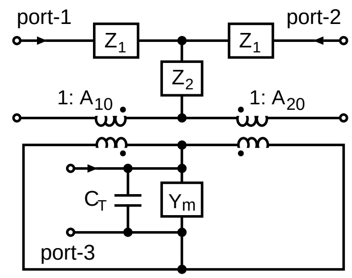


Figure 3: Equivalent circuit model of IDT

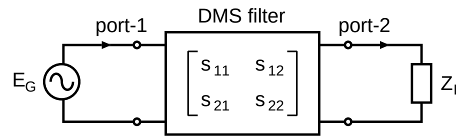


Figure 4: Two-port network model of DMS filter

to a finite value. Therefore, we introduce a minimum unit value e_i $(i = 1, \cdots, n)$ into each of the decision variables $x_i \in \mathbf{x}$. Then we suppose that every decision variable takes a discrete value within the region bounded by its parametric limitations as follows.

$$\underline{x}_i \leq x_i \leq \overline{x}_i, \quad i = 1, \cdots, n. \tag{1}$$

where, $(\overline{x}_i - \underline{x}_i) \mod e_i \equiv 0, \ e_i > 0.$

2.2 Modeling and Simulation

In order to analyze the frequency response characteristics of DMS filters based on the computer simulation, we derive their complete models. For example, the behavior of each IDT composing the DMS filter in Fig. 1 can be analyzed by using a three-port circuit illustrated in Fig. 3, where port-1 and port-2 are acoustic ports, and port-3 is electric port[10]. Also each SMSA can be modeled by a similar circuit. Since the components of a usual DMS filter, such as IDTs and SMSAs, are connected acoustically in cascade on a piezoelectric substrate, the entire circuit model of the DMS filter can be made up from components' equivalent circuits[9]. Then terminating acoustic ports of the circuit with characteristic impedance, the two-port network model of the DMS filter is obtained with four scattering coefficients s_{ij} as shown in Fig. 4.

Among the scattering coefficients in Fig. 4, s_{11} and s_{22} are often referred as reflection coefficients. On the other hand, s_{12} and s_{21} are referred as transmission coefficients, where the relation $s_{12} = s_{21}$ always holds for DMS filters. These scattering coefficients s_{ij} are complex numbers depending on decision variables $\mathbf{x} = (x_1, \cdots, x_n)$ and frequency ω.

3 Problem Formulation

3.1 Criteria of Frequency Response

In order to evaluate the performance of DMS filters, we use three criteria of their frequency response characteristics. First of all, from the above reflection coefficients s_{ii} $(i = 1,\ 2)$ in Fig. 4, standing wave ratios Γ_1 and Γ_2 are defined for the input- and output-ports of the network model of DMS filter as follows.

$$\left[\begin{array}{lcl} \Gamma_1(\mathbf{x},\,\omega) & = & \dfrac{1+|s_{11}(\mathbf{x},\,\omega)|}{1-|s_{11}(\mathbf{x},\,\omega)|} \\[2ex] \Gamma_2(\mathbf{x},\,\omega) & = & \dfrac{1+|s_{22}(\mathbf{x},\,\omega)|}{1-|s_{22}(\mathbf{x},\,\omega)|} \end{array}\right. \tag{2}$$

Besides them, from the transmission coefficient s_{21}, the attenuation Γ_3 is also defined as follows.

$$\Gamma_3(\mathbf{x},\,\omega) = -20\,\log(|s_{21}(\mathbf{x},\,\omega)|) \tag{3}$$

Now, the performance of DMS filters is specified by using the upper and lower bounds of the above three criteria Γ_h $(h = 1,\ 2,\ 3)$. Let Ω be a set of frequencies $\omega \in \Omega$ sampled from the remarkable frequency range of a target DMS filter including its passing- and stop-bands. $\Gamma_h(\mathbf{x},\,\omega)$ denotes the value of the criterion Γ_h evaluated at $\omega \in \Omega$ with a given vector of decision variables $\mathbf{x} = (x_1,\,\cdots,\,x_n)$. By using the upper $U_h(\omega)$ and the lower $L_h(\omega)$ bounds, $\Gamma_h(\mathbf{x},\,\omega)$ is restricted at each $\omega \in \Omega$ as follows.

$$L_h(\omega) \le \Gamma_h(\mathbf{x},\,\omega) \le U_h(\omega), \quad h = 1,\ 2,\ 3. \tag{4}$$

Consequently, in the structural design of DMS filters, we have only to minimize the following objective function derived from the constraints in (4).

$$f(\mathbf{x}) = \sum_{\omega\in\Omega} \frac{\nabla U(\mathbf{x},\,\omega) + \nabla L(\mathbf{x},\,\omega)}{|\Omega|} \tag{5}$$

$$\left[\begin{array}{lcl} \nabla U(\mathbf{x},\,\omega) & = & \displaystyle\sum_{h=1}^{3} \max\{\,\Gamma_h(\mathbf{x},\,\omega) - U_h(\omega),\,0\,\} \\[3ex] \nabla L(\mathbf{x},\,\omega) & = & \displaystyle\sum_{h=1}^{3} \max\{\,L_h(\omega) - \Gamma_h(\mathbf{x},\,\omega),\,0\,\} \end{array}\right.$$

3.2 Optimum Design of DMS Filter

The structural design of a DMS filter is formulated as an optimization problem. Let $\mathcal{X}$ be the search space of solutions, namely the whole set of possible decision variables $x_i \in \mathbf{x}$ constrained by (1). For minimizing the objective function $f(\mathbf{x})$ in (5), the optimization problem can be described mathematically as follows.

$$\left[\begin{array}{ll} \text{minimize} & f(\mathbf{x}) \\ \text{subject to} & \mathbf{x} \in \mathcal{X} \end{array}\right. \tag{6}$$

4 Free & Freeze Method

4.1 Neighborhood

The neighborhood $N(\mathbf{x})$ is generally a set of solutions that resemble the solution $\mathbf{x} \in \mathcal{X}$[11]. We adopt the k-degree-neighborhood $N_k(\mathbf{x})$ $(k \le n)$ that is defined as follows[6]: every solution $\mathbf{x}' \in N_k(\mathbf{x})$ differs from the solution $\mathbf{x}$ in just k elements, and the difference between elements $x_i' \in \mathbf{x}'$ and $x_i \in \mathbf{x}$ is equivalent to their minimum unit value as $e_i = |x_i' - x_i|$. For solving the optimization problem in (6), Variable Neighborhood Search (VNS) explores several neighborhoods $N_k(\mathbf{x})$ $(k = 1,\,\cdots,\,\overline{k})$, and jumps from there to a new one if and only if an improvement was made. Therefore, the locally optimal solution $\mathbf{x}^\star \in \mathcal{X}$ found by VNS is defined exactly as follows.

$$f(\mathbf{x}^\star) \le f(\mathbf{x}),\ \ \forall \mathbf{x} \in \bigcup_{k=1}^{\overline{k}} N_k(\mathbf{x}^\star) \cap \mathcal{X}. \tag{7}$$

Since VNS guarantees only to find a locally optimal solution defined by (7), the quality of the final solution seems to be improved by searching a lot of neighborhoods. However, the computational time spent by VNS increases with the number of them. Exactly, the total number of solutions included in neighborhoods $N_k(\mathbf{x})$ $(k = 1,\,\cdots,\,\overline{k})$ rises drastically with the maximum degree of neighborhood $\overline{k}$ and the number of decision variables n as follows.

$$|\bigcup_{k=1}^{\overline{k}} N_k(\mathbf{x})| = \sum_{k=1}^{\overline{k}} |N_k(\mathbf{x})| = \sum_{k=1}^{\overline{k}} 2^k\,{}_nC_k \tag{8}$$

4.2 Move Strategy

Since VNS investigates more than one neighborhood, it is important to settle the order of them in the search. A unique search strategy named the introvert search is used in the VNS proposed by authors[6]. Conventional VNSs look for an improvement moving from the smallest neighborhood to the largest one[12]. On the other hand, the proposed introvert VNS (I-VNS) takes a contrary motion in the search. As a result, I-VNS can hardly fall into poor optima, because it copes well with the problem of epistasis[13], i.e., the synergistic relation between different variables.

4.3 Selection Rule

As we have mentioned previously, Free & Freeze method is a kind of the divide-and-conquer method. So, it divides the search space of an optimization problem into two segments, namely free-segment and freeze-segment, and applies the above I-VNS to the free-segment. First of all, an incumbent $\mathbf{x}$ of I-VNS is regarded as a set of decision variables $x_i \in \mathbf{x}$ and divided into two subsets such as $\mathbf{x} = \mathbf{x}^F \cup \mathbf{x}^Z$. From now on, $x_i \in \mathbf{x}^F$ are called "free-variables" and $x_j \in \mathbf{x}^Z$ are called "freeze-variables". The values of the freeze-variables are fixed until the procedure of exclusive I-VNS ends. On the other hand, the values of the free-variables are changed by I-VNS for improving the objective function's value $f(\mathbf{x})$.

In order to choose the free-variables $x_i \in \mathbf{x}^F$ from a solution $\mathbf{x}$ in Free & Freeze method, we can use the designer's knowledge about the design problems of DMS filters. Furthermore, for choosing the free-variables $x_i \in \mathbf{x}^F \subseteq \mathbf{x}$ automatically, we propose three selection-rules, namely "random", "sensitivity analysis" and "epistasis analysis". In the random selection-rule, the free-variables $x_i \in \mathbf{x}^F$ are chosen randomly. On the other hand, in the sensitivity analysis and the epistasis analysis selection-rules, every decision variable $x_i \in \mathbf{x}$ $(i = 1, \cdots, n)$ included in a solution $\mathbf{x}$ is given its priority $p(x_i)$ detailed later. Then some free-variables $x_i \in \mathbf{x}^F$ are chosen from $x_i \in \mathbf{x}$ according to their priorities.

In order to decide the priority $p(x_i)$ for a decision variable $x_i \in \mathbf{x}$, the sensitivity analysis selection-rule evaluates the effect of the small change of the decision variable $x_i \in \mathbf{x}$ on the objective function's value. Therefore, the priority $p(x_i)$ is defined as follows.

$$p(x_i) = |\nabla f(x_i)|, \quad i = 1, \cdots, n. \tag{9}$$

$$\left[\begin{array}{rcl} \nabla f(x_i) & = & f(x_1, \cdots, x_i + e_i, \cdots, x_n) \\ & & -f(x_1, \cdots, x_n) \end{array} \right.$$

In addition to the sole effect of x_i evaluated in (9), epistasis analysis selection-rule considers the synergetic effect caused by the simultaneous changes of two different variables $x_i \in \mathbf{x}$ and $x_j \in \mathbf{x}$ $(j \neq i)$. Therefore, the priority $p(x_i)$ is defined as follows.

$$p(x_i) = \max\{\hat{p}(x_i), |\nabla f(x_i)|\} \tag{10}$$

$$\left[\begin{array}{rcl} \hat{p}(x_i) & = & \max_j\{|\nabla f(x_i, x_j) - \nabla f(x_j)|\} \\ \nabla f(x_i, x_j) & = & f(x_1, \cdots, x_i + e_i, \cdots \\ & & \cdots, x_j + e_j, \cdots, x_n) \\ & & -f(x_1, \cdots, x_n), \quad j \neq i. \end{array} \right.$$

In Free & Freeze method, the period of executing I-VNS one time is called "stage". Besides the total number of stages $\overline{m}$, the maximum degree of neighborhood $\overline{k}_m$ and the number of free-variables n_m $(1 \leq n_m \leq n)$ need to be specified for each stage

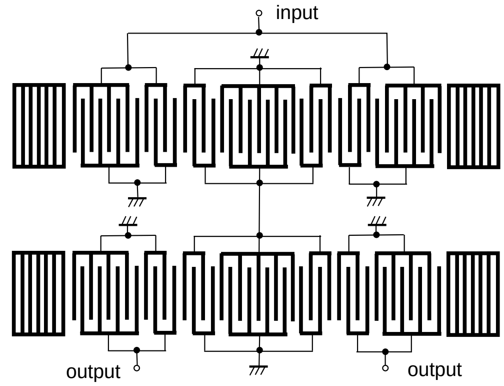


Figure 5: Tandem type DMS filter

m $(m = 1, \cdots, \overline{m})$. Therefore, the strategy of Free & Freeze method means a set of the above $(\overline{m} \times 2 + 1)$ parameters coupled with the selection-rules of free-variables, namely, random, sensitivity analysis, epistasis analysis and the knowledge of designer.

In the following procedure of Free & Freeze method, the k-degree-neighborhood $N_k(\mathbf{x}^F)$ is defined as well as the conventional $N_k(\mathbf{x})$. Also a subset $D_k(\mathbf{x}^F) \subseteq N_k(\mathbf{x}^F)$ is defined as shown in (11).

$$\begin{array}{l} D_k(\mathbf{x}^F) = \{\, \mathbf{x}'^F \in N_k(\mathbf{x}^F) \cap \mathcal{X} \mid \\ \qquad f(\mathbf{x}'^F \cup \mathbf{x}^Z) < f(\mathbf{x}^F \cup \mathbf{x}^Z) \,\} \end{array} \tag{11}$$

[**Free & Freeze method**]

Step 1: Get an initial solution $\mathbf{x} \in \mathcal{X}$. Let $m := 1$.

Step 2: Select n_m variables $x_i \in \mathbf{x}$ for $\mathbf{x}^F \subseteq \mathbf{x}$.

Step 3: Let $k := \overline{k}_m$.

Step 4: If $D_k(\mathbf{x}^F) \neq \emptyset$, choose $\mathbf{x}'^F \in D_k(\mathbf{x}^F)$, let $\mathbf{x}^F := \mathbf{x}'^F$ and go back to *Step 3*.

Step 5: If $k = 1$ holds, let $\mathbf{x} := \mathbf{x}^F \cup \mathbf{x}^Z$. Otherwise, let $k := k - 1$ and go back to *Step 4*.

Step 6: If $m = \overline{m}$ holds, return $\mathbf{x}$ and end. Otherwise, let $m := m + 1$ and go back to *Step 2*.

5 Experimental Results

5.1 Problem Instances

Free & Freeze method was applied to the structural design of a tandem type DMS filter shown in Fig. 5. The tandem type DMS filter consists of two DMS filters connected before and after. Furthermore, each of the DMS filters consists of nine components, namely seven IDTs and two SMSAs. Therefore, in order to

Table 1: Search space of tandem DMS filter

i	$\underline{x}_i$,	$\overline{x}_i$	e_i	i	$\underline{x}_i$,	$\overline{x}_i$	e_i
1	250,	350	10	13	250,	350	10
2	10.0,	20.0	0.5	14	10.0,	20.0	0.5
3	15.5,	25.5	1.0	15	15.5,	25.5	1.0
4	1.0,	3.0	1.0	16	1.0,	3.0	1.0
5	150,	250	10	17	150,	250	10
6	0.0,	0.8	0.1	18	0.0,	0.8	0.1
7	3.0,	7.0	0.5	19	3.0,	7.0	0.5
8	3.0,	7.0	0.5	20	3.0,	7.0	0.5
9	9.1,	10.0	0.1	21	9.1,	10.0	0.1
10	10.0,	10.6	0.1	22	10.0,	10.6	0.1
11	395,	399	1	23	395,	399	1
12	19.8,	20.2	0.2	24	19.8,	20.2	0.2

Table 2: Strategy in experiment 1

m	1	2	3	4
n_m	24	12	12	12
$\overline{k}_m$	1	3	3	3

Table 3: Strategy in experiment 2

m	1	2	3	4
n_m	12	6	6	6
$\overline{k}_m$	1	3	3	3

decide a suitable structure of the tandem type DMS filter in Fig. 5, we have to consider $n = 24$ decision variables $x_i \in \mathbf{x}$ $(i = 1, \cdots, n)$, which are similar to the design parameters illustrated in Fig. 2.

Table 1 shows the search space $\mathcal{X}$ of the optimization problem, namely the upper and lower bounds of $n = 24$ decision variables $x_i \in \mathbf{x}$ and their minimum unit values e_i $(i = 1, \cdots, n)$. In order to define the objective function $f(\mathbf{x})$ in (5), the upper and lower bounds of three criteria $\Gamma_h(\mathbf{x}, \omega)$ $(h = 1, 2, 3)$ were specified at 120 frequency points $\omega \in \Omega$.

5.2 Experiment 1

In order to decide the suitable structure of the tandem type DMS filter shown in Fig. 5, Free & Freeze method was applied to the above optimization problem. The strategy described in Table 2 was employed for Free & Freeze method. Furthermore, either one of three automatic selection-rules, namely random, sensitivity analysis and epistasis analysis, was used to choose n_m $(n_m \leq n)$ free-variables $x_i \in \mathbf{x}^F$.

Table 4 shows the experimental results in which three automatic selection-rules were compared in the objective function's values of the final solutions (f_{min}) and the total numbers of examined solutions (no. of $\mathbf{x}$). From Table 4, Free & Freeze method combined with sensitivity analysis investigated so many

Table 4: Results of experiment 1

selection	f_{min}	no. of $\mathbf{x}$
random	10.77	7525
sensitivity	5.13	10879
epistasis	9.86	4714

Table 5: Results of experiment 2

selection	f_{min}	no. of $\mathbf{x}$
random	12.58	1558
sensitivity	9.85	1040
epistasis	10.74	2594

solutions that it could find the best solution. Therefore, it can be say that sensitivity analysis made the best selection of free-variables $x_i \in \mathbf{x}^F$. On the other hand, random selection-rule did not work so well in spite of the number of examined solutions.

5.3 Experiment 2

By using the designer's knowledge about the structure of the tandem type DMS filter in Fig. 5, two-step design approach was employed. In the first design step, decision variables $x_i \in \mathbf{x}$ $(i = 13, \cdots, 24)$ were chosen for free-variables $x_i \in \mathbf{x}^F \subseteq \mathbf{x}$, while $x_j \in \mathbf{x}$ $(j = 1, \cdots, 12)$ were chosen for freeze-variables $x_j \in \mathbf{x}^Z \subseteq \mathbf{x}$. Then the structure of the output-side single DMS filter was optimized exclusively. On the other hand, in the second design step, $x_j \in \mathbf{x}$ $(j = 1, \cdots, 12)$ were chosen for free-variables, while $x_i \in \mathbf{x}$ $(i = 12, \cdots, 24)$ were chosen for freeze-variables. Then the structure of the input-side DMS filter was optimized exclusively. In both of the two optimization problems, the strategy in Table 3 was employed for Free & Freeze method.

Table 5 shows the experimental results of the two-step design approach in the same way with Table 4. From the results in Table 5, Free & Freeze method combined with sensitivity analysis selection-rule found the best solution again. Furthermore, from Table 4 and Table 5, it can be say that the manual selection of free-variables $x_i \in \mathbf{x}^F$ based on the designer's knowledge is efficient to reduce the computational time spent by Free & Freeze method without losing the quality of final solutions so much.

Figure 6 shows the attenuation $\Gamma_3(\mathbf{x}^\star, \omega)$ about the final solution $\mathbf{x}^\star$ obtained by Free & Freeze method combined with sensitivity analysis in Table 5. In Fig. 6, the attenuation of the initial solution is also plotted by one-broken line. Furthermore, the upper $U_3(\omega)$ and the lower $L_3(\omega)$ bounds of the criterion Γ_3 are plotted by two-broken line. From the frequency response characteristics shown in Fig. 6, we can con-

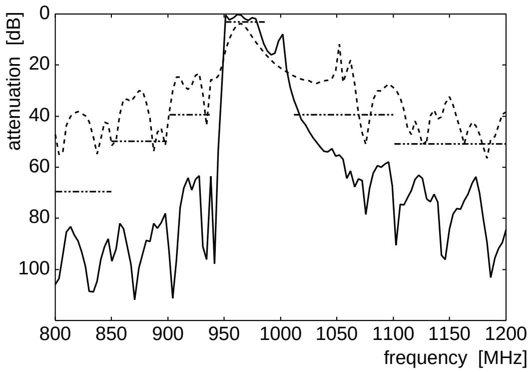


Figure 6: Frequency responses (attenuation)

firm that the final solution obtained by using the proposed technique almost meets the specifications.

6 Conclusion

In this paper, for solving the large-scale design problems of complex DMS filters in short periods, a new optimization technique named Free & Freeze method was proposed. In the proposed method, the search space of an optimization problem was divided repeatedly into two segments, namely free-segment and freeze-segment. Then an efficient local search named I-VNS was applied to the free-segment. Furthermore, for choosing several free-variables from decision variables, three automatic selection-rules, namely random, sensitivity analysis and epistasis analysis, were presented. From the experimental results conducted on a tandem type DMS filter, it developed that the sensitivity analysis selection-rule was superior to the other rules in the quality of final solution.

Future work will focus on the planning of the dexterous strategies for Free & Freeze method. Because Free & Freeze method is applicable to the optimum design problems of various SAW devices, appropriate strategies based on the designer's knowledge about respective SAW devices become more important.

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