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Multi-Objective Robust Parameter Design Methodology Applied to Microwave Circuit

Takafumi Nakagawa and Tasuku Kirikoshi.

Abstract— **this paper presents a useful robust parameter design methodology for a microwave circuit. A set of design values is decided to satisfy the specification and to reduce the effect of variability in manufacture. The multi-objective problem is treated as a single optimization problem. The function which shows the variability from the ideal relationship between signal and response is minimized under the limiting conditions based on the specifications. We have used the iterative technique with the Monte Carlo method to search the controllable values. Taguchi's OA is used to consider the noise factors dealing with the production tolerance. The proposed method is applied to the design of a microwave amplifier, and its effectiveness is studied with the computer simulation and experiments. The first run rate achieved 97 % in the manufactures of a microwave amplifier.**

Index Terms—**Robust Design, Microwave circuit, multi-objective optimization, SN ratio**

I. Introduction

THE robust design is an important technology that provides an acceptable product to the variability in a first run and upgrade product quality at low cost. The computer aided engineering (CAE) can be used as an alternative to assist product design in many cases of microwave circuit designs. The conventional techniques using a statistical or a worst-case modeling have been usually used by many designers [1], [2], [3], [4]. In these works, the designers decide parameters to satisfy the specifications. After that, they ascertain a degree of the variability of the objective function by a Monte Carlo approach or an experimental design method. In order to accept the variability in the performance, the conventional design tries to obtain the best performance. But in this case it is unknown whether it shows the small variability until the manufacture. Moreover, in the microwave circuit, considering the tradeoff between a frequency response, gain, noise figure, power consumption, VSWR and the cost, the design leads to a multi-objective problem. At present, a simulated annealing algorithm (SA) and a stochastic algorithm based on evolution theory such as genetic algorithms (GA) are usually used to solve this problem by many engineers [5], [6], [7]. When using these traditional methods, it generally takes much CPU time to determine the optimal settings of design values. Many approaches have been studied to reduce the CPU time, such as optimization methods based on orthogonal design [8], [9] or multi-objective optimization techniques finding the pareto front of trade-off functions [10], [11], [12], [13]. However, these works did not consider the effects of noises which were an important part of the philosophy of the robust design. The conventional approach by Dr. Taguchi has been well known as the quality control to improve the performance of the products at a low cost [14], [15], [16]. Dr. Taguchi employs an orthogonal array (OA) to arrange the experiments and uses signal-to-noise ratios (SN ratio) to evaluate the variability of response in an experimental run. But Dr. Taguchi's method has a limitation because his method is an additive linear model and incompatible with a multi-objective problem. Several approaches have been presented to apply this method to the multiple-objective problems [17], [18], [19], [20], [21]. However, these works can not prevent trapping in a local minimum without reaching global optimization. Other techniques such as a response-surface methodology have been studied for the designs of microwave circuits [22], [23], [24]. In these works the regression techniques are used to fit the recorded response values to a user-defined model. As a result, much computing time is required to decide the fitting function when a number of designable factors and objectives becomes large. The method using GA combined with Taguchi's method is also proposed to consider the effects of noises [25], [26]. In these works, the quality loss function is minimized with OA which includes the noises. GA is one of the efficient methods to find the required global minimum. But it is difficult to find the better results which cross the initial objective values. An effective interactive technique for solving multi-objective problems is also proposed [27], [28]. The trade-off between objective functions is analyzed with newly defined trade-off matrix, and the pareto front is calculated by using a global optimization method.

As a consequence, the many multi-objective optimization methods considering production tolerance are proposed, but it is still in the research stage. In this paper, a useful robust design methodology for the microwave circuit design is presented. The validity of this method is studied in the application to a microwave amplifier.

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II. Proposed Methodology

The multi-objective problem is treated as a single optimization problem. The variability from the ideal relationship between signal and response is minimized under the limiting conditions based on the specifications of the objective functions. SN ratio is used to evaluate the robustness of the function which describes the ideal performance of a circuit. The multi-objective problem is described by the formulation (1).

$$\text{Maximize } \eta(\hat{x}) \quad \text{Subject to } \hat{x} \in X = \{\hat{x} \in R^m \mid g_i(\hat{x}) \le 0, (i = 1, \cdots, m)\} \tag{1}$$

$\eta(\hat{x})$ is SN ratio about a function $f_1(\hat{x})$ which describes an ideal performance of the system. $\eta(\hat{x})$ varies with a set of controllable factors; $\hat{x} = (x_1, \cdots, x_s)$ .The suffix, s, is the number of controllable factors. R^m is the feasible region and $g_i(\hat{x})$ denotes a limiting condition for each objective function of $f_1(\hat{x}), f_2(\hat{x}), \cdots, f_m(\hat{x})$, where the symbol, m , is the kinds of objective functions. η is calculated by equation (2) [28];

$$\eta = 10 \cdot \log(\beta^2 / \sigma^2) \tag{2}$$

The slope, β, is determined by the least squares method of y_{ij} on M^*_i as follows;

$$\beta = \sum_j \beta_j / q \tag{3}$$

$$y_{ij} = \beta_j M^*_i + e_{ij}, i = 1, \cdots, p; j = 1, \cdots, q \tag{4}$$

where M^*_i is the average of $\sum_j y_{ij}$ and e_{ij} is the regression error. *j* refers to the number of experiments in OA of the noise factors. *i* is the number of calculations for each set of controllable factors. The variance from the regression line, σ^2, is given by

$$\sigma^2 = \frac{\sum_{j=1}^{k}\sum_{i=1}^{n}((\beta_j - \beta) * M^*_i)^2 + \sum_{j=1}^{k}\sum_{i=1}^{n}(y_{ij} - \beta_j M^*_i)^2}{(pq-1) * q * \sum_i M^{*2}_i} \tag{5}$$

when all y_{ij} coincides with M^*_i, β is equal to one. The controllable parameter set is searched under the satisfaction of the limiting conditions. The objective functions are calculated by a random search of controllable values with a Monte Carlo method. We have used the iterative technique instead of conventional optimal methods. This reason is to find the many pareto results to prevent the recalculation when the specification has changed. Taguchi's OA is used to consider the noise factors dealing with the production tolerance. The proposed method searches a set of design values in a direction which increases SN ratio. The bigger SN ratio gives the smaller variability from equation (2). The procedure runs in the following steps and the detail is shown in Fig.1.

Step 1: Assign the noise factors to Taguchi's OA.

Step 2: In the first step, a set of controllable factors $\hat{x}$ is searched from a whole range, randomly;

$$x_i = \text{rand}\,(0,1) \times (x_{i,high} - x_{i,low})$$

In the following steps, $\hat{x}$ is selected from the range of ±Δ%, randomly .

$$x_i = w_i \times \text{rand}\,(-\Delta \quad, \Delta);$$

where w_i is the previous values of x_i , Δ is a range width to search .

Step 3: Calculate the objective functions $f_i(\hat{x})$ for each experiment number of OA and each set of controllable factor $\hat{x}$.

Step 4: When max ($\eta(\hat{x})$) is larger than the previous η_0 under the satisfaction of the limiting conditions, w_i is replaced by x_i in the following step. If there was not a desirable result, the width of Δ is reduced by a half of the previous value.

Step 5: Eventually, a set of controllable parameters which gives the maximum SN ratio is selected among the calculated results.

```
( assign the  noise factor s to the OA)
do k= 1 ,n; ( n is a number of iterations.)
   do i=1,p  ; ( p is a number to search x̂ in each step k.)
      If k=1 then
            do r=1,s; x_ir = rand (0,1) ×(x_r,high − x_r,low) ; end do;
      else do r=1,s; x_ir = w_ir ×rand (−Δ_k ,+Δ_k) ; end do;
      end If;
      x̂ =(x_i1 , …, x_is ) ;
      do j=1, q; ( q is the  experimental number in OA )
         calculate the target function   f_i (x̂)
      end do;
   end do;
   calculate η(x̂);
   If ( η= ∃k (max(η(x̂)_k ) >η_0) ∧( ∀k )(g_i (x̂)_k ≤0,(i =1,…,m )} Then
      set w_i = x_i ; η_0 = η ;
   else
         Δ_k =0.5* Δ_k-1 ;
   end If;
end do;
( end of  calculation )
```

Fig. 1. Algorithm of the proposed method.

III. Application to Microwave Amplifier

An input matching-circuit of a microwave amplifier is designed by the proposed method. Figure 2 shows a layout of an amplifier with FETs. The CAE model of a half of Fig.2 is illustrated in Fig.3. The input signal is divided into four circuits through the input matching-circuit and amplified by the four FET in parallel. All signals are combined with the output matching-circuit. It is important to reduce the variance of gain in order to realize the high performance. The commercial CAE code is used to calculate the performance of the circuit shown in Fig.3.

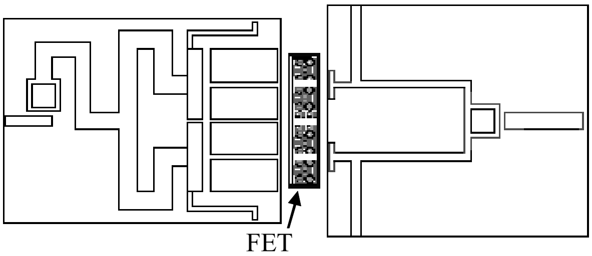

Fig. 2. Layout architecture of microwave amplifier.

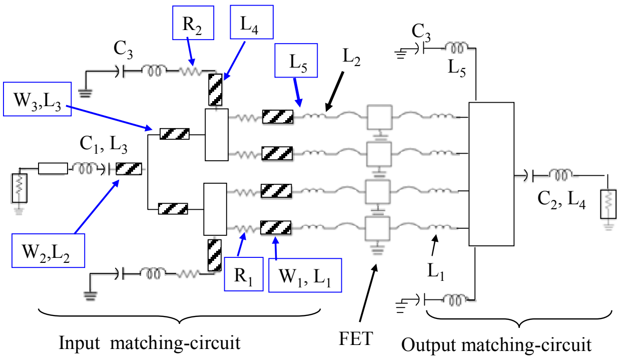

Fig. 3. Schematic drawing of CAE model. The ten kinds of noise factors and the nine kinds of the controllable factors are described in this model. The controllable factors are expressed with the symbols enclosed in the squares.

A. *Identifying Noise and Controllable Factors*

The ten kinds of noise factors and the nine kinds of controllable factors are considered in this design. The noise factors are selected and tabulated in Table I. The symbols of "A" to "J" correspond to the following; "A" and "B" are the manufacturing tolerances in the thickness and the permittivity of a base plate, respectively. "C" and "D" are the production tolerances of the inductance of lines connecting to FETs. "E" and "F" relate to the variations of inductance on the DC cut-off circuit, and "H" and "I" give the manufacturing tolerances of the capacitance of both the input and the output DC cut-off circuits. "G" is the variation of the inductance of the microstrip line connecting to the capacitor and "J" is the manufacturing tolerance of a capacitance of a bypass capacitor. Taguchi's OA is used to decrease the amount of calculations. Ten kinds of noise factors are assigned to OA of L12 (2^{11}) as shown in Table II. The number in Table II denotes the noise levels described in Table I. The nine kinds of controllable factors are selected and they are shown in Fig.3 as the symbols enclosed in the squares. The controllable factors are three kinds of the length, L_1, L_2, L_3, and the width, W_1,W_2, W_3, on the microstrip lines and the gate wire inductance, L_5, connecting to a FET. In addition, the resistace of R_1 and R_2 are considered to stabilize the performance of the circuit. The manufacturing tolerances of these factors are not taken into account due to the very small production error. The FET is modeled by the measured S parameters. The calculation is done by a linear computation.

B. *Calculations*

The main performance of an amplifier and its target specification is shown in Fig.4. The horizontal and vertical axes show the frequency and the gain, respectively, where FL and FH indicate the low and high frequency within the range of use. The dotted line is the minimum of the target value. The deviation caused by the noise factors is shown in Fig. 5. The vertical line denotes the normalized gain which is expressed by the following equation (5);

$$\tilde{Gain} = 10^{(\overline{gain} - Target)/10} \qquad (5)$$

where $\overline{gain}$ is the averaged gain at each frequency. In Fig.5, the solid line indicates the averaged value and the vertical dotted symbol shows the deviation produced by the noise factors. When the gain is equal to the target value, normalized gain agrees with 1.0. Our target is to decide the

TABLE I
NOISE FACTORS

	Noise factors	Level$_1$	Level$_2$
A	thickness	-10%	10%
B	permittivity	-10%	10%
C	inductance L_1	-10%	10%
D	Inductance L_2	-10%	10%
E	inductance L_3	-0.06nH	0.06nH
F	Inductance L_4	-0.06nH	0.06nH
G	Inductance L_5	-0.06nH	0.06nH
H	capacitance C_1	-20%	20%
I	capacitance C_2	-20%	20%
J	capacitance C_3	-20%	20%

TABLE II
OA OF L12 (2^{11})

No	1	2	3	4	5	6	7	8	9	10	11
1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	2	2	2	2	2	2
3	1	1	2	2	2	1	1	1	2	2	2
4	1	2	1	2	2	1	2	2	1	1	2
5	1	2	2	1	2	2	1	2	1	2	1
6	1	2	2	2	1	2	2	1	2	1	1
7	2	1	2	2	1	1	2	2	1	2	1
8	2	1	2	1	2	2	2	1	1	1	2
9	2	1	1	2	2	2	1	2	2	1	1
10	2	2	2	1	1	1	1	2	2	1	2
11	2	2	1	2	1	2	1	1	1	2	2
12	2	2	1	1	2	1	2	1	2	2	1

Ten kinds of noise factors are assigned to OA. The number in matrix denotes the noise levels described in Table I

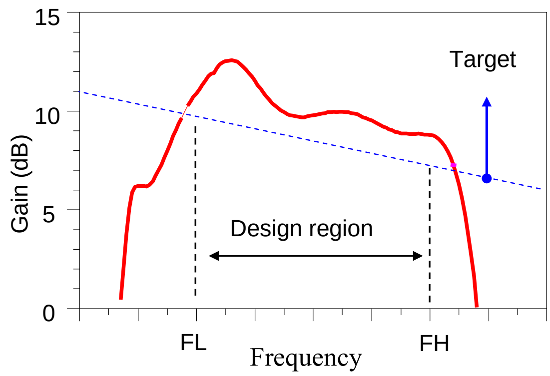

Fig. 4. The main performance of an amplifier and its target. The dotted line is a minimum of a target value.

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values of controllable factors which can make the deviation from averaged gain smaller. The stabilization coefficient of this amplifier is also considered as a condition of the limitation.

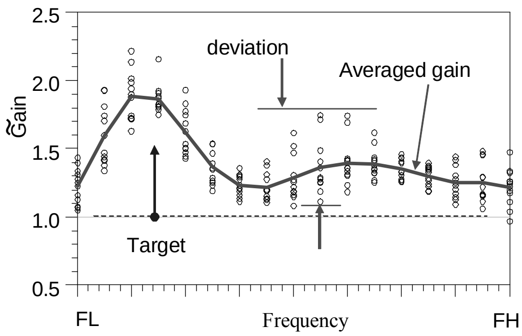

Fig. 5. The main performance of the amplifier and its targeted value. The vertical line denotes the normalized gain.

IV. Results and Discussionns

Fig.6 shows the calculated results. The horizontal line gives the SN Ratio, η , and the vertical line shows the minimum value of $\widetilde{Gain}$. The 100 points are plotted for each of ten iterations. In the first step, the initial value is decided with the uniform random search in the whole range of controllable factors. In the second step, the range width is set as Δ=50%. In the following steps, Δ is changed with the range width shown in Fig.7. From Fig.6, the calculated results gradually converge to the value which gives a larger SN ratio. The proposed method is also compared with the results described by the symbol of ●, which are calculated by SA algorithm. The proposed method searches the pareto front. It also shows that η has a tradeoff toward a gain. Fig.7 shows the relationship between η and the number of iterations. The horizontal line denotes the number of iterations. The vertical lines show the η and Δ. η increases from 35.8 db in the initial step to 43.1 db in the final result. This means that the variation decreased to a 0.43 of an initial value expressed with the coefficient of variation. The calculation is converged by 10 iterations. CPU time is 360 sec with Intel Core i5-2500 processor in a Windows PC. Although the number of calculated points is 100 on each iteration step, the designer can change it depending on the distribution of results.

Fig.8 shows the frequency response of gain at the design points "A" ～"D" shown in Fig.6. "A" and "D" give the minimum and the maximum of SN ratios in Fig.6. "B" gives the maximum gain, and "C" shows the final design. Fig.8 shows that the larger SN ratio gives the smaller variance of the gain. The design "C" is selected to achieve the target value even if the worst case production occurred.

The initial configuration was modified under the limitation on the substrate size. The response of the circuit was confirmed by the electromagnetic field computation, and it was tuned to avoid the undesirable oscillations. We have manufactured the prototype amplifier based on this result. The frequency response of the prototype is compared with the calculation in Fig.9. In Fig.9, the bold line shows the measurement and the flux of thin lines are the calculations which include the variance caused by the noise

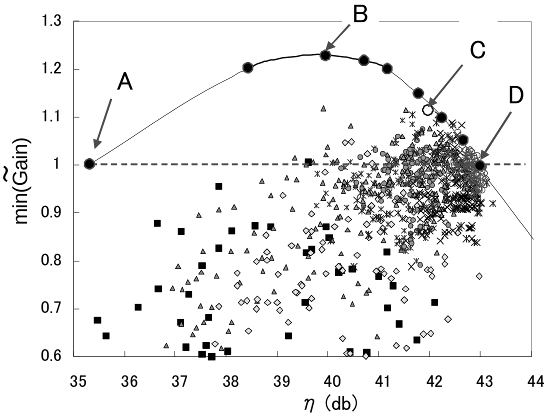

Fig. 6. Calculated results. The 100 points are plotted for each of ten iterations. In the first step, the initial value is decided by the random search in the design space. In the following steps, the scale ranges are decreased by the half of the previous ones.

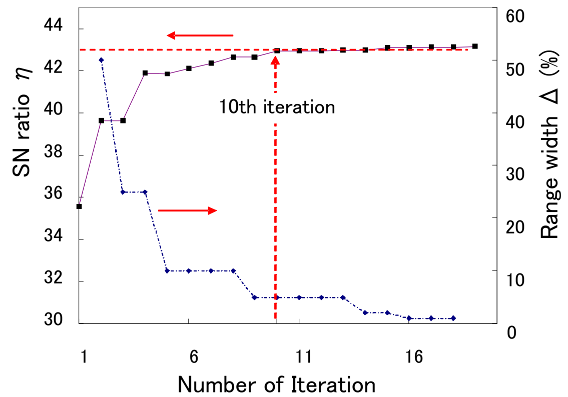

Fig. 7. The relationship between SN ratio, η , and range width, Δ , corresponding to the number of iteration.

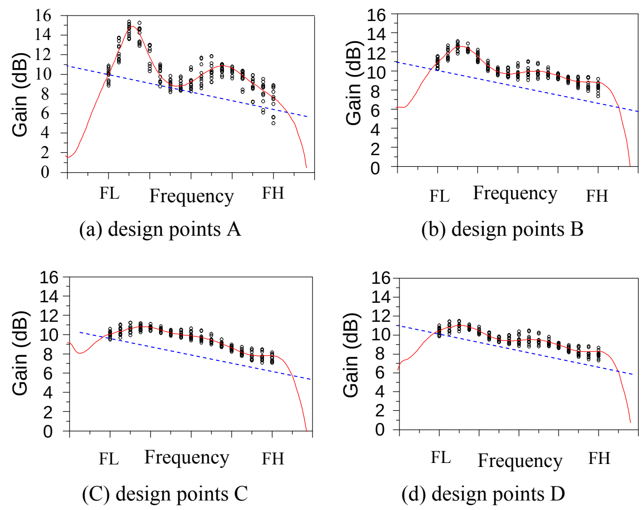

Fig.8. The frequency response of gain for the design points on Fig,6.

factors. The calculated result agrees with the measurement qualitatively, and the gain satisfies the specification.

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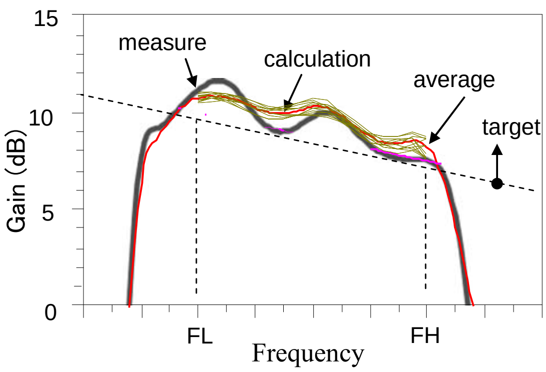

Fig. 9. Comparison between the calculation and the experiment. The bold line is the measurement and the flux of thin lines are the calculations

The experimental gain in the mass production is plotted in Fig.10. The maximum and the minimum value correspond to the minimum and the maximum gain in all experiments, respectively. The average gain was ±0.6 dB and the standard deviation was 0.2 dB. The first run rate obtained 97 %.

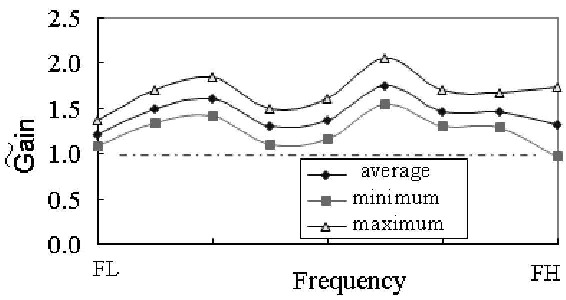

Fig. 10. Normalized gain obtained by the experiments in the manufactures.

V. Conclusion

A useful robust parameter design methodology is proposed for a microwave circuit. A set of design values is decided to satisfy the specification and to reduce the variability of the performance in the manufacture. The multi-objective problem is treated as a single optimization problem. The function which shows the variability of the ideal relationship between signal and response is minimized under the limiting conditions based on the specifications. The proposed method is applied to the design of a microwave amplifier, and its effectiveness is studied with the CAE simulation and the experiments. It results that the first run rate achieved 97 % in the manufactures.

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