Robust Parameter Design Methodology for Microwave Circuits Considering the Manufacturing Variations

Takafumi Nakagawa and Tasuku Kirikoshi

Abstract—**Our target is to achieve a higher first run rate in the quantity production of microwave circuits. For this purpose, we propose a useful robust parameter design methodology in which the multi-objective problem is treated as a single optimization problem under limiting conditions. A set of controllable factors, which provide an acceptable production, is calculated by considering such noise factors as manufacturing variations. We used the iterative technique with the Monte Carlo method to search for these values. The noise factors are assigned to Taguchi's orthogonal array to reduce the CPU time. Our proposed method is applied to the design of a microwave amplifier. This method's performance is compared with four optimization methods in the microwave circuit simulation, and its effectiveness is experimentally confirmed. The calculated controllable factors are not unique among these optimization methods to minimize the variations of the gain in manufactures. Our method is more efficient to find many candidates than the other optimization methods. The produced amplifiers have achieved a first run rate of 97% in its manufacture.**

Index Terms—**robust design, microwave circuit, multi-objective optimization, SN ratio**

I. Introduction

Robust design is an important technology that provides an acceptable product for variability in a first run and upgrades product quality at low cost. Computer aided engineering (CAE) can be used as an alternative to assist product design in many cases of microwave circuit designs. Conventional techniques using statistical or worst-case modeling have been usually used by many designers [1], [2], [3], [4]. In these works, they ascertain the degree of the performance variability by the Monte Carlo approach or an experimental design method after deciding the parameters. The conventional design tries to find the values of the controllable factors for the allowance of manufacturing variations. But it is unknown whether it gives smaller variability until the manufacturing is completed. Moreover, considering the tradeoff among frequency response, gain, noise figure, power consumption, VSWR, and cost, the design leads to a multi-objective problem. At present, the simulated annealing algorithm (SA) and a stochastic algorithm based on evolution theory such as genetic algorithms (GA) are usually used to solve the multi-objective problem [5], [6], [7]. When using these traditional methods, it generally takes much CPU time to determine the optimal values. Therefore, many approaches have reduced the CPU time using optimization methods based on orthogonal design [8], [9] or techniques finding the pareto front of tradeoff functions [10], [11], [12]. However, these works did not consider the effects of noises, which are an important part of the philosophy of robust design. The conventional approach by Taguchi is well known as the quality control to improve the performance of products at low cost [13], [14], [15]. Taguchi employed an orthogonal array (OA) to arrange the experiments and used signal-to-noise ratios (SN ratio) to evaluate the variability of response in an experimental run. But Taguchi's method has a limitation because it is an additive linear model and is incompatible with the multi-objective problem. Several approaches have been applied to multiple-objective problems [16], [17], [18], [19], [20]. However, these works cannot prevent trapping in a local minimum without reaching global optimization. Other techniques such as response-surface methodology have been studied for the designs of microwave circuits [21], [22], [23]. In these works, regression techniques are used to fit the recorded response values to a user-defined model. As a result, computing time is greatly required to decide the fitting function when the number of designable factors and objectives becomes large. A method using GA combined with Taguchi's method was also proposed to consider the effects of noises [24], [25]. In these works, the quality loss function is minimized with OA assigned noise factors. Another effective interactive technique for solving multi-objective problems has been proposed [26], [27], where the tradeoff between objective functions is analyzed with a newly defined tradeoff matrix, and the interactive multi-objective design optimization based on the Satisficing Trade-Off Method is used.

In this paper, we propose a useful robust design methodology for microwave circuit design and apply it to the design of a microwave amplifier. The validity of this method is studied with computer simulations and experiments.

Takafumi Nakagawa is with Advanced Technology R&D Center, Mitsubishi Electric Corporation, 8-1-1, Tsukaguchi-Honmachi, Amagasaki, Hyogo, JAPAN (corresponding author to provide phone: +81-06-6497-7245;fax:+81-06-6497-7288;e-mail:Nakagawa.Takafumi@dr.MitsubishiElectric.co.jp).

Tasuku Kirikoshi is with Communication Systems Center, Mitsubishi Electric Corporation, 8-1-1, Tsukaguchi-Honmachi, Amagasaki, Hyogo, JAPAN (corresponding author to provide phone: +81-06-6496-9882; fax:+81-06-6496-9735;e-mail:Kirikoshi.Tasuku@ap.MitsubishiElectric.co.jp).

(Advance online publication: 26 May 2012)

II. Robust Parameter Design Methodology

We treat the multi-objective problem as a single optimization problem [28]. We calculate the sets of design values under the limiting conditions based on the specifications. The Taguchi's SN ratio is used to evaluate the robustness of a circuit's ideal performance. The multi-objective problem is evaluated by the following formulation (1):

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

where $\eta(\hat{x})$ is the SN ratio, which describes the variability of the performance. The performance is described by a function of $f(\hat{x}, M)$. $\hat{x} = (x_1, \cdots, x_s)$ is a set of controllable factors, and M is the input signal. Suffix s refers to the number of controllable factors. R^m is the feasible region, and $g_i(\hat{x})$ denotes the limiting condition. m is the number of objective functions which refer to the specifications. η is calculated by Eq. (2) [20]:

$$\eta = 10 \cdot \log(\beta^2 / \sigma^2) . \quad (2)$$

Slope β is determined by the least-squares method of y_{ij} :

$$\beta = \sum_j \beta_j / q \quad (3)$$
$$y_{ij} = \beta_j M^*_i + e_{ij}, i = 1, \cdots, p; j = 1, \cdots, q \quad (4)$$
$$M_i^* = \sum_j y_{ij} / q , \quad (5)$$

where M^*_i is the average of calculations for all noise. and e_{ij} is the regression error. j refers to the experimental runs in OA. i refers to the number of input signals. The total square error from regression line σ^2 is given by

$$\sigma^2 = \frac{\sum_{j=1}^{k}\sum_{i=1}^{n}((\beta_j - \beta) * M^*_i)^2 + \sum_{j=1}^{k}\sum_{i=1}^{n}(y_{ij} - \beta_j M^*_i)^2}{(pq-1) * q * \sum_i M^{*2}_i} . \quad (6)$$

When each y_{ij} coincides with M^*_i, β_j equals one.

The objective functions are calculated against the controllable factors decided with the Monte Carlo method. Taguchi's OA is used to consider the noise factors to reduce the CPU time. The proposed method searches for the optimal values in the direction that increases the SN ratio. A bigger SN ratio gives smaller variability from Eq. (2). The procedure runs in the following steps, and its details are shown in Fig. 1.

Step 1: Assign the noise factors to Taguchi's OA.
Step 2: In the first step, set of controllable factors x_i is randomly searched with the Monte Carlo method in the range of $[x_{i,high}, x_{i,low}]$:

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

After the second step, x_i is randomly selected in the range of [-Δ, Δ]:

$$x_i = w_i \times \text{rand}(0,1) \times [-\Delta, \Delta] ,$$

where w_i is the previous values of x_i and Δ is a search strip width.
Step 3: Calculate objective functions $f(\hat{x}, M)$ for each experimental number of OA and set of controllable factors $\hat{x}$.
Step 4: When max $[\eta(\hat{x})]$ is larger than the previous one under the satisfaction of the limiting conditions, w_i is replaced by x_i. If there was no desirable result, the width of Δ% is reduced by half of the previous one.
Step 5: A set of controllable parameters, which gives the maximum SN ratio, is selected among the calculated results.

```
( assign noise factors to OA)
do k= 1 ,n; ( n is the 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 target function f_i (x̂,M)
    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 proposed method

III. Application to Microwave Amplifier

We designed an input matching circuit for a microwave amplifier with our proposed method. Fig. 2 shows the layout of an amplifier with FETs. The schematic drawing of a CAE model is illustrated in Fig. 3. The input signal is divided into four circuits through the input matching circuit and amplified by four FETs in parallel. All signals are combined with the output matching circuit. It is important to reduce the variance of gain for stable performance. Commercial CAE code [29] is used to calculate the performance of the microwave circuit.

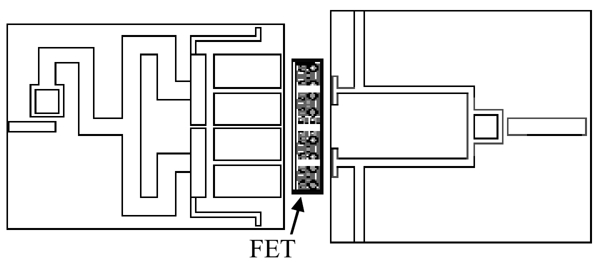


Fig. 2 Layout architecture of microwave amplifier

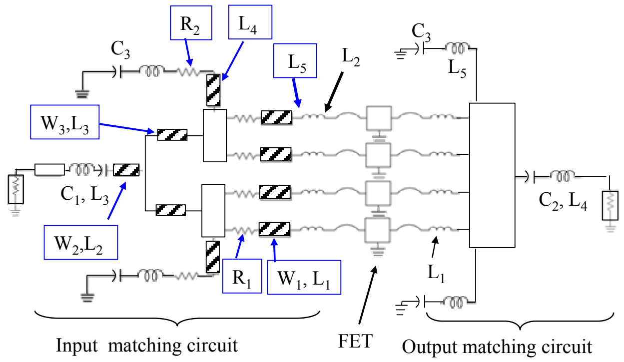


Fig. 3 Schematic drawing of CAE model. Ten kinds of noise factors and nine kinds of controllable factors are illustrated. Controllable factors are expressed with symbols enclosed in squares.

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 noise factors are assigned to OA. Number in matrix denotes noise levels described in Table I.

A. *Identifying Noise and Controllable Factors*

Ten kinds of noise factors and nine kinds of controllable factors are illustrated in Fig. 3. The noise factors are tabulated in Table I, where "A" and "B" are the manufacturing variations of the thickness and the permittivity of the base plate. "C" and "D" are the manufacturing tolerances about the inductance of the lines connected to FETs. "E" and "F" are related to the variations of inductance on the DC cut-off circuit, and "H" and "I" are the manufacturing tolerances of the capacitors of both input and output DC cut-off circuits. "G" is the variation of the inductance of the microstrip line connecting the capacitor, and "J" is the manufacturing tolerance of the bypass capacitors. Ten kinds of noise factors are assigned to OA of L12 (2^{11}) in Table II, where the number denotes the noise levels described in Table I.

In Fig,3, nine kinds of controllable factors are described as symbols enclosed in the squares. The controllable factors are lengths L_1, L_2, and L_3 and widths W_1, W_2, and W_3 on the microstrip lines and gate wire inductance L_5 connected to each FET. In addition, two kinds of resistance, R_1 and R_2 , are optimized. The FET is modeled by measured S parameters. The calculation is done by a linear computation.

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	-0.06 nH	0.06 nH
F	Inductance L_4	-0.06 nH	0.06 nH
G	Inductance L_5	-0.06 nH	0.06 nH
H	capacitance C_1	-20%	20%
I	capacitance C_2	-20%	20%
J	capacitance C_3	-20%	20%

B. *Calculations*

We applied the proposed method to a design of microwave amplifier. A performance example and its target specification are shown in Fig. 4. FL and FH indicate the low and high frequency within the range of use. The dotted line shows the lower limit of a 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 Eq. (6):

$$\widetilde{Gain} = 10^{(\overline{gain} - Target)/10} \qquad (6)$$

where $\overline{gain}$ is the averaged gain at each frequency. In Fig. 5, the solid line indicates the averaged value and the vertical dotted symbols show the deviation produced by the noise factors. When the gain is equal to the target value, the normalized gain agrees with one. The SN ratio is calculated with a linearized function. Fig. 6 shows an example of an evaluation. The calculated data for the experimental run of No. 5 in Table II are plotted by dotted circles, which are expressed with regression line $y_{i5} = \beta_5 * M_i$. A straight dotted line refers to the averaged gain calculated with the experimental runs. If data of No. 5 agree with the averaged values, slope β_5 equals 1.0. These procedures are done for all experimental runs in Table II, and the SN ratio is calculated from (2). In this design, RF stabilization coefficient k of a power amplifier is also considered as a limiting condition.

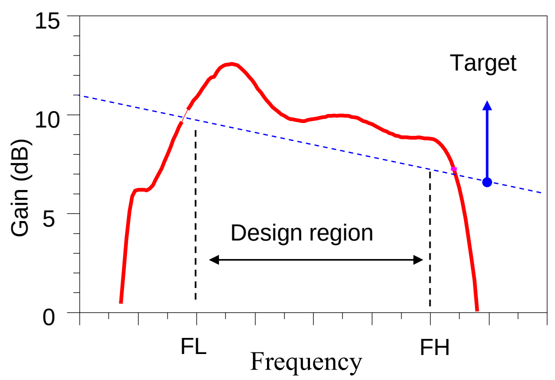


Fig. 4 Example of performance and its target in a microwave amplifier. Dotted line is a minimum of a target value.

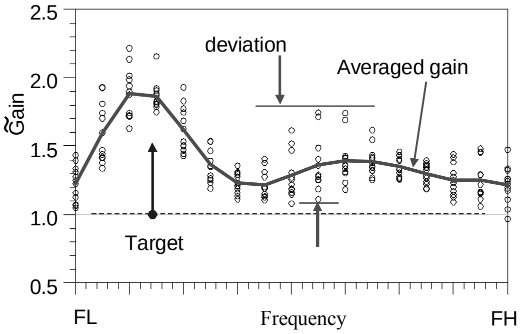


Fig. 5. The example of the performance in the amplifier, and its targeted value. The vertical line denotes the normalized gain.

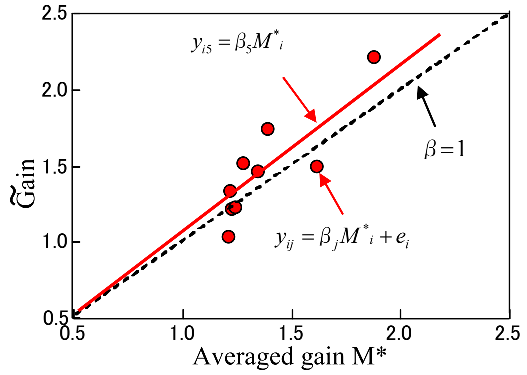


Fig. 6 Example of evaluation for SN ratio using a linearized function

IV. Results and Discussion

Figure 7 shows the calculated results by the iterative technique with the Monte Carlo method. The horizontal line gives SN Ratio η , and the vertical line shows the minimum value of $\widetilde{Gain}$. 100 points are plotted for each of ten iterations. Plotted symbols ● are the calculated results with SA. At the initial step, search strip width Δ is set as half of the nominal values. In the following steps, Δ decreases as shown in Fig. 8, which shows the relationship between SN ratio η and Δ for the each of iterations. From Fig. 7, the calculated results gradually converge to the pareto front calculated by SA. This shows the effectiveness of our method. In Fig. 8, η increases from 35.8 to 43.1. This means that the coefficient of variation decreased to 43% of the initial one. The calculation is almost converged by ten iterations, and its CPU time is 360 sec with Intel Core i5-2500 processor in a Windows PC.

We also compared the calculated results with gradient search (GR), SA and GA in the commercial CAE code [29], [30]. Fig. 9 compares the optimal values, which are tabled in Table III. Initial design shows the values without considering the effects of the noise factors. The optimal values are different among the optimization methods; the calculated result is not unique. This means that many combinations of parameters can reduce the effect of manufacturing variations. Therefore, we must find many candidates for the change of specifications, and for this purpose the random search method with the Monte Carlo method is more efficient than the other optimization algorithms.

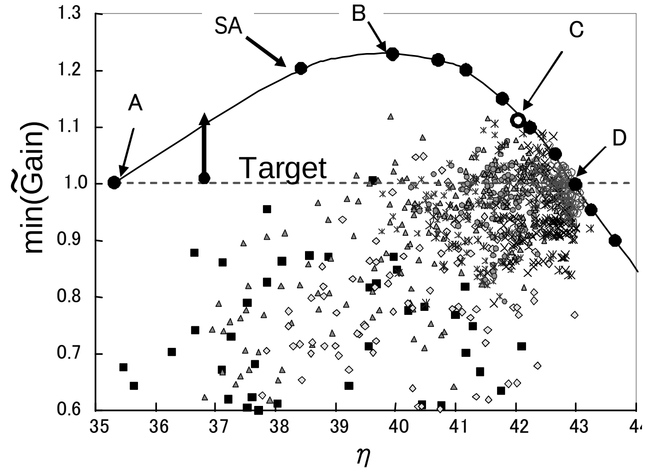


Fig. 7 Calculated results by iterative technique with Monte Carlo method. 100 points are plotted for each of ten iterations. In the first step, initial value is decided by random search in the entire design space. In following steps, search ranges are decreased by half of previous one.

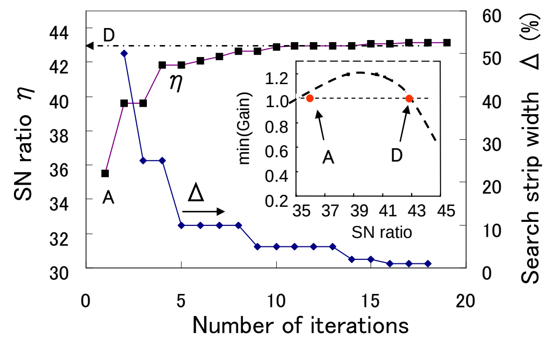


Fig. 8 Relationship between SN ratio η and search strip width Δ corresponding to number of iterations

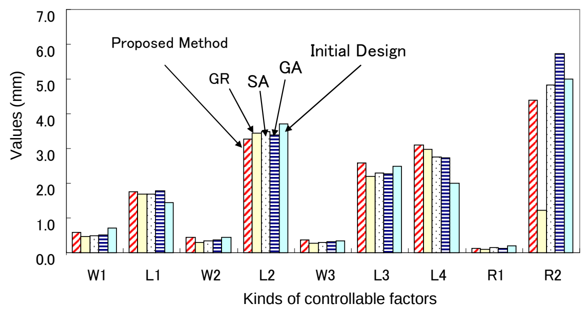


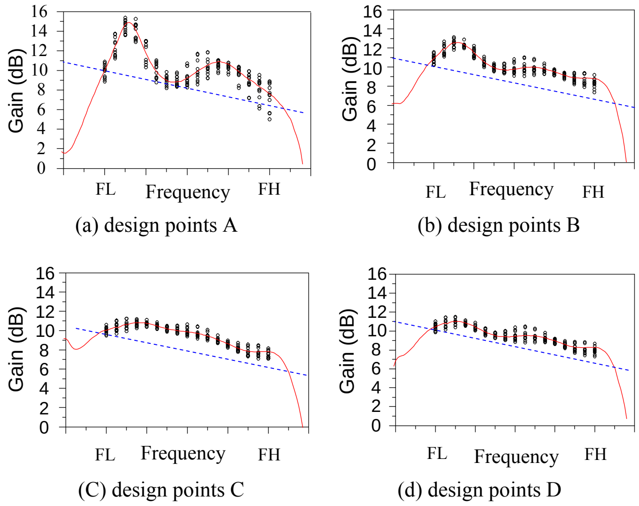
Fig. 9 Comparison of optimal values of controllable factors among three optimization methods. Gradient method is a gradient search and SA method is a simulated annealing algorithm. GA is a genetic algorithm. Initial design shows design values without considering effects of noise factors. Theses controllable factors are described in Fig.3.

TABLE III
COMPARISONS OF OPTIMAL VALUES

Controllable Factors	SN	W_1	L_1	W_2	L_2	W_3	L_3	L_4	R_1	R_2
Initial Design	39.6	0.70	1.45	0.45	3.70	0.35	2.50	2.00	0.20	5.00
Proposed Method	43.1	0.60	1.75	0.45	3.27	0.36	2.59	3.10	0.11	4.39
GR	43.1	0.45	1.68	0.30	3.44	0.28	2.21	2.98	0.11	1.21
SA	43.3	0.49	1.69	0.34	3.50	0.30	2.28	2.77	0.14	4.84
GA	43.1	0.52	1.79	0.36	3.39	0.33	2.27	2.74	0.11	5.74

Controllable factors are described in Fig.3.

Figure 10 shows the frequency response of gain at design points “A” ～”D” in Fig. 7. “A” and “D” give the minimum and the maximum of the SN ratio. “B” gives the maximum gain, and “C” shows the final design. From Fig. 10, the larger SN ratio gives smaller variance of gain. Design “C” is selected to achieve the target value even if the worst case production occurred.



(a) design points A (b) design points B

(C) design points C (d) design points D

Fig. 10 Frequency response of gain for design points on Fig. 7

The final configuration on the basal plate was decided for under the limitation of the substrate size. The circuit response was confirmed by electromagnetic field computation, and it was tuned to avoid the undesirable oscillations in the CAE model. We manufactured the prototype amplifier based on these results. The calculated results are compared with the experiments in Fig. 11. The bold line shows the measurement, and the flux of thin brown lines are the calculations that include the variance caused by the noise factors. The calculated result qualitatively agrees with the measurement, and the gain satisfies the specification.

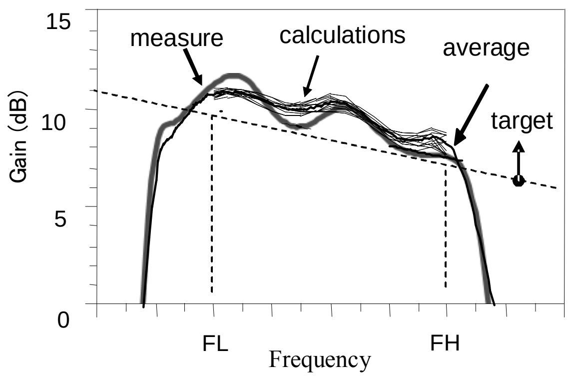


Fig. 11 Comparison between calculation and experiment. Bold line is measurement and flux of brown thin lines are calculations

The measured gain in the mass production is plotted in Fig. 12. The maximum and minimum values correspond to the minimum and maximum gain in all measurements, respectively. The variability of average gain was within ± 0.6 dB, and the standard deviation was 0.2 dB. These microwave amplifiers have achieved a first run rate of 97% in the manufactures.

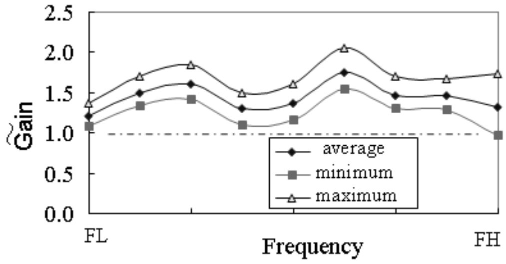


Fig.12 Normalized gain obtained by experiments in manufacturing

V. Conclusion

We proposed a robust parameter design methodology for microwave circuits considering manufacturing variations. We calculated a set of controllable factors, which provide acceptable production, by considering such noise factors as manufacturing variations. The multi-objective problem is treated as a single optimization problem under the limiting conditions based on the specifications. We applied our proposed method to the design of a microwave amplifier and studied its effectiveness with CAE simulations and experiments. The microwave amplifiers designed by our proposed method have achieved a first run rate of 97% in the manufactures.

Acknowledgment

The authors are grateful to Dr. M. Shimozawa and Dr. M. Miyazaki, and the first author also wishes to thank Dr. Haruna for their many valuable comments and suggestions.

References

[1] Shuich. Ota, *Reliability Engineering Association of Japan (REAJ)*, Vol. 25, No. 8, 2003, pp. 865-868, (in Japanese)

[2] N. Shigyo, H. Tanimoto, T. Morishita, K. Sugawara, N. Wakita, and Y. Asahi, “Statistical simulation of MOSFETs using TCAD: meshing noise problem and selection of factors,” *3rd International Workshop on Statistical Metrology*, 1998, pp. 10-13

[3] Stephen W., Peter Feldmann, and Kannan Krishna, “Statistical Integrated Circuit Design,” *IEEE Journal of Solid-State Circuits*, Vol. 28. No. 3, 1993, pp. 193-202

[4] Norman J. Elias, “Acceptance Sampling: An Efficient, “Accurate Method for Estimating and Optimizing Parametric Yield,” *IEEE Journal of Solid-Stats,* Vol. 29. No. 3, 1994, pp. 323-327

[5] Ricardo S. Zebulum, Marco Aurélio Pacheco, and Marley Vellasco, “A Multi-Objective Optimization Methodology Applied to the Synthesis of Low-Power Operational Amplifiers,” *Proceedings of the XIII International Conference in Microelectronics and Packaging,* Vol. 1.,1998, pp. 264-271

[6] Leonard C. Brito and Paul H. P. de Carvalho, “An evolutionary approach for multi-objective optimization of nonlinear microwave circuits,” *IEEE MTT-S International Microwave Symposium Digest*, Vol. 2, 2004, pp. 949-952

[7] Eckart Zitzler and Lothar Thiele, “Multiobjective Evolutionary Algorithms: A Comparative Case Study and the Strength Pareto Approach,” IEEE Transactions on evolutionary Computation, Vol. 3, No. 4, 1994, pp. 257-271

[8] Lingling Sun, Zhi Zhou, Xungen Li and Wenming Zhao, “A new optimization method for microwave broad band amplifier based on orthogonal design,” *Proceedings. 6th International Conference on Solid-State and Integrated-Circuit Technology*, 2001, pp. 1151-1154

[9] Hiroyuki KAWAGISHI and Kazuhiko KUDO, “Development of Grobal Optimization Method by Orthogonal Array (Application to Mechanical Design Problem),” *The Japan Society of Mechanical Engineering*, 2007, pp. 2335-2342

[10] Fatemeh Kashfi, Safar Hatami, and Massoud Pedram, “Multi-objective optimization techniques for VLSI circuits, “*IEEE*

12th International Symposium on Quality Electronic Design, 2011, pp. 156-163
[11] Tadashi Kurokawa, "Trade-off Analysis Method," *TOSHIBA Review* Vol. 60, No. 1, 2005, pp. 48-51 (in Japanese)
[12] Sawal Ali, Beuben Wilcock, Peter Wilson, and Andrew Brown, "Yield Model Characterization for Analog Integrated Circuit Using Pareto-Optimal Surface," *IEEE International Conference on Electronics, Circuits, and Systems*, 2008
[13] Genichi Taguchi, "Taguchi methods in LSI fabrication process," *6th International Workshop on Statistical Methodology*, 2001, pp. 1-6
[14] Genichi Taguchi and Shih-Chung Tsai, "Quality Engineering (Taguchi Methods). For The Development of Electronic Circuit Technology," *IEEE Transactions on Reliability*, Vol. 44, No. 2, 1995, pp. 225-229
[15] R. D. Kulkarni and Vivek Agarwal, "Taguchi Based Performance and Reliability. Improvement of an Ion Chamber Amplifier for Enhanced Nuclear Reactor Safety," *IEEE Transactions on Nuclear Science*, Vol. 55, No. 4, 2008, pp. 2303-2313
[16] Kun-Lin Hsieh, Lee-Ing Tong Hung-Pin Chiu and Hsin-Ya Yeh, "Optimization of a multi-response problem in Taguchi's dynamic system," *Computers & Industrial Engineering* Vol. 49, 2005, pp. 556–571
[17] Lee-Ing Tong, Chung-Ho Wang, Chih-Chien Chen, and Chun-Tzu Chen, "Dynamic multiple responses by ideal solution analysis," *European Journal of Operational Research*, Vol. 56, No. 16, 2004, pp. 433–444
[18] Hsu-Hwa Chang, "A data mining approach to dynamic multiple responses in Taguchi experimental Design," *Expert Systems with Applications*, Vol. 35, 2008, pp. 1095-1103
[19] V N Gaitondea, S R Karnikb, B T Achyuthac, and B Siddeswarappad, "Multi-response optimization in drilling using Taguchi's quality loss function," *Indian Journal of Engineering & Materials Science*s, Vol. 13, No. 6, 2006, pp. 484-48
[20] Ful-Chiang Wu, Bing-Chang Ouyang, Cheng-Hsiung Chen, and Chi-Hao Yeh, "Robust design of nonlinear dynamic problem," *2nd International Conference on Education Technology and Computer (ICETC)*, 2010, pp. V1-162-166
[21] Jim Carroll and K and Ghang, "Statistical Computer-Aided Design for Microwave Circuits," *IEEE Transactions on Microwaves and Technology*, Vol. 44, No.1, 1992, pp. 24-32
[22] Young, D. L., Teplik, J., Weed, H. D., Tracht, N. T., and Alvarez, A. R., " Application of statistical design and response surface methods to computer-aided VLSI device design II. Desirability functions and Taguchi methods," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, Vol. 10, 1991, pp. 103-115
[23] Ming-Ru Chen, "Robust design for VLSI process and device," *6th International Workshop on Statistical Methodology*, 2001, pp. 7-16
[24] Pisvimol Chatsirirungruang, "Application of Computer Aided Engineering with Genetic Algorithm and Taguchi method in Nonlinear Double-Dynamic Robust Parameter Design," *Proceedings of the International MultiConference of Engineers and Computer Scientists*, 2010, pp.17-19
[25] Pisvimol Chatsirirungruang and Masami Miyakawa, "Application of genetic algorithm to numerical experiment in robust parameter design for signal multi-response problem," *Journal of Management Science and Engineering Management*, Vol. 4, No. 1, 2009, pp. 49-59
[26] H. Nakayama, "Proposal of Satisfying Trade-Off Method for Multiobjective Programming," *Journal of the Society of Instrument and Control Engineers*, Vol. 20, No. 1, 1984, pp. 29-35 (in Japanese)
[27] S. Kitayama, K. Yamazaki, M. Arakawa, H. Yamakawa, "Trade-Off Analysis on the Multi-Objective Design Optimization," *Transactions of the Japan Society of Mechanical Engineers*, Part C, 75(754), 2009, pp.1828-1836 (in Japanese)
[28] Takafumi Nakagawa and Tasuku Kirikoshi, "Multi-Objective Robust Parameter Design Methodology Applied to Microwave Circuit," *Proceedings of The International Multi Conference of Engineers and Computer Scientists 2012 (IMECS 2012)*, pp. 973-978, Hong Kong
[29] Advanced Design System (ADS) in Agilent Technologies, URL: http://www.home.agilent.com/agilent/product.jspx?nid=-34346.0.00&cc=US&lc=eng
[30] Tuning, Optimization, and Statistical Design Manual in Agilent Technologies,URL:http://newport.eecs.uci.edu/eceware/ads_docs/pdf/optstat.pdf