A Robust Design of MMIC using Taguchi Method

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Abstract

In this paper, we demonstrate a robust design of Monolithic Microwave Integrated Circuits (MMIC) using the Taguchi Method. In accordance with the Taguchi Method, noise factors, which are uncontrollable sources of variation, and control factors, which are available to control both the deviations and the mean-values by circuit designers, were assigned to an orthogonal array. We simulated radio frequency (RF) characteristics by the orthogonal array. For an optimization procedure, we evaluated a criterion for stability (Taguchi Method's signal-to-noise ratio) and a criterion for average values (Taguchi Method's sensitivity). In order to realize this design approach, we have developed a modified Angelov Model to take those factors into the non-linear equivalent circuit parameters of a transistor (Tr). To demonstrate the effectiveness of the technique, we first designed a MMIC using the center value of the factors as a conventional method. Next, we designed another MMIC by this new method focusing on the improvement of the variation and the average value of linear gain characteristics. We fabricated both MMICs and evaluated the distribution of the linear gain characteristics. As a result, we have successfully improved the signal-to-noise ratio (SN) by +3.7 dB, the standard deviation by -33%, and the average value by +0.7 dB. Furthermore, we also optimized the saturated output power (Psat), which is a nonlinear characteristic. Simulation results indicated the improvement of the distribution and the average of the Psat.

INTRODUCTION

The Taguchi Method is a powerful tool to reduce development time and to stabilize production yield in a product development process. As MMIC die sizes have been reduced in recent years, a larger variation of RF characteristics can occur in production due to even small process variations. Therefore, ensuring quality stability of the products becomes more difficult and the yield of the RF characteristics may become unstable in mass production.

The Taguchi method is an experimental technique for optimizing the design parameters of the process or product to minimize the effect of the noise factors which cause variations in characteristics. It has following 5 features:

#1. Two-step design, minimizing the variation first then adjusting the average value to the target value.

#2. 2 indexes introduced, one is "SN ratio" for stability and the other is “sensitivity" for the average value. Higher SN ratio means higher stability.

#3. Intentional introduction of noise factors in order to simulate the variations.

#4. Optimization of the control factors to keep an ideal state whatever the combinations of the noise factors would be. The control factors such as physical dimensions can be chosen by the designers.

#5. Utilizing the design of experiments (DOE) with the orthogonal array allocated to the both noise and design parameters (Figure 1) and the Graph of Factorial Effects generated with the SN ratio and sensitivity, which tells us visually the optimum control factors. (Figure 2)

Using a conventional design methodology, we were forced to repeat the circuit design and the trial production, because we designed with only the center values of RF characteristics and evaluated the distribution at the actual trial production stage to ensure the yield stability. In contrast, the Taguchi method enables the estimation of the variation of each noise factor at the simulation phase. Additionally, control factors satisfying the desired RF characteristics and yield stability are visually obtained by using the Graphs of Factorial Effects. To realize this approach, we used the orthogonal array, which can obtain simulation results with good accuracy and efficiency using an optimal number of combinations. For iterative calculation, we have developed calculation modules reading the array from the outside of a commercial simulator.

In this paper, we report on our use of the Taguchi Method to optimize MMIC circuit designs and significantly reduce the variation of RF characteristics in volume production.

15

An orthogonal array / The experimental results

No.	Control factors					Noise factors					SN ratio (dB)	Sensitivity (dB)
	•••	A	B	C	•••	•••	a	b	c	•••		
1	•••	1	1	1	•••	•••	1	1	1	•••	η_1	S_1
2	•••	1	1	1	•••	•••	2	2	2	•••	η_2	S_2
3	•••	1	1	1	•••	•••	3	3	3	•••	η_3	S_3
4	•••	1	1	1	•••	•••	3	3	2	•••	η_4	S_4
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
n	•••	3	2	1	•••	•••	1	1	3	•••	η_n	S_n

Figure 1. The orthogonal array and the results chart for the design of experiment

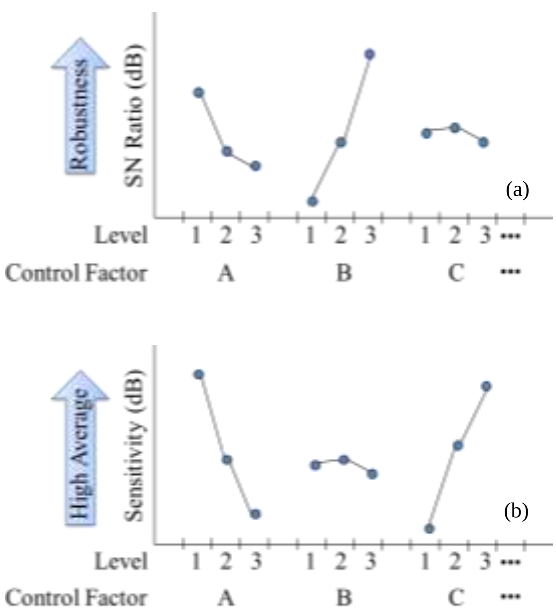


Figure 2. Graphs of Factorial Effects example

SIMULATION TECHNIQUE USING THE ORTHOGONAL ARRAY

To calculate the variation of the MMIC RF characteristics, a combination of control factors and noise factors must be first identified. Initially we tried to make use of the built-in capabilities of the existing commercial simulator. However using only ten factors exceeded the calculation capacity of the simulator since the function tried to carry out every combination of the factors. Obviously 10 factors are not enough for a large circuit simulation. Therefore we chose to investigate the orthogonal array of the Taguchi Method, which can provide the simulation results with good accuracy and efficiency using a limited number of combinations.

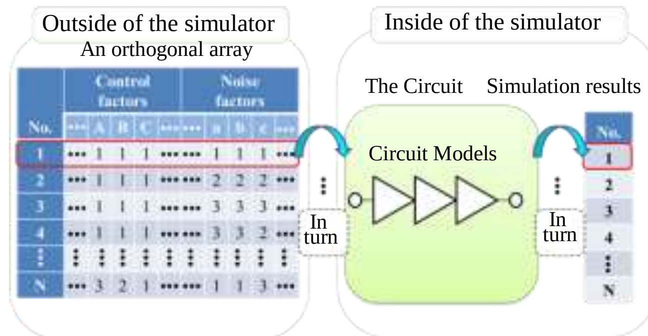
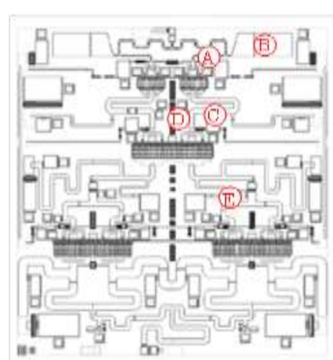


Figure 3. Simulation technique using the orthogonal array

Since the existing simulator doesn't support the orthogonal array directly, we have developed new calculation modules which read the combinations of factors from the orthogonal array outside of the simulator and perform the repeated calculation as shown in Figure 3. With this new simulation technique, even though we carried out the combination of calculations using a large scale L108 x L108 Array with 98 factors (49 control factors + 49 noise factors), it required only 20% of the calculation capacity of the simulator. This number of factors is sufficient for the large scale MMIC circuit design.

DESIGN APPROACH & IMPROVEMENT EFFECTS

The conventionally designed MMIC using the center value of factors is shown in Figure 4. We have modified this circuit with the goal of improving of the variation and the average of a linear gain using the Taguchi Method. First, we chose 10 factors as the noise factors including such transistor parameters as the transconductance (Gm), Gate-Source capacitance (Cgs), and gate resistance (Rg), as shown in Figure 5, as well as physical parameters such as the substrate



A: Line #1 Length
B: Line #2 Width
C: Area of the MIM capacitor #1
D: Area of the MIM capacitor #2
E: Line #3 Length
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Figure 4. The circuit layout of the power amplifier
Chip size: 2.6 x 3.0 mm, GaAs substrate thickness: 28 um, Frequency: 13.7 – 14.5 GHz

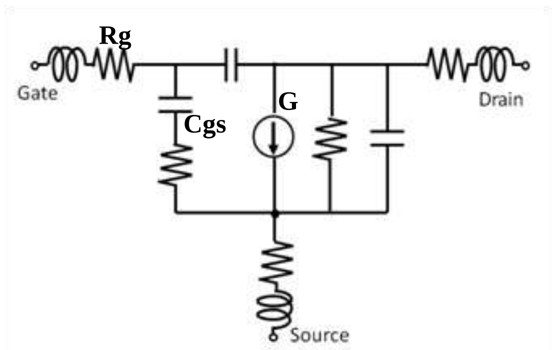

Figure 5. The nonlinear equivalent circuit model of a transistor (Angelov Model)

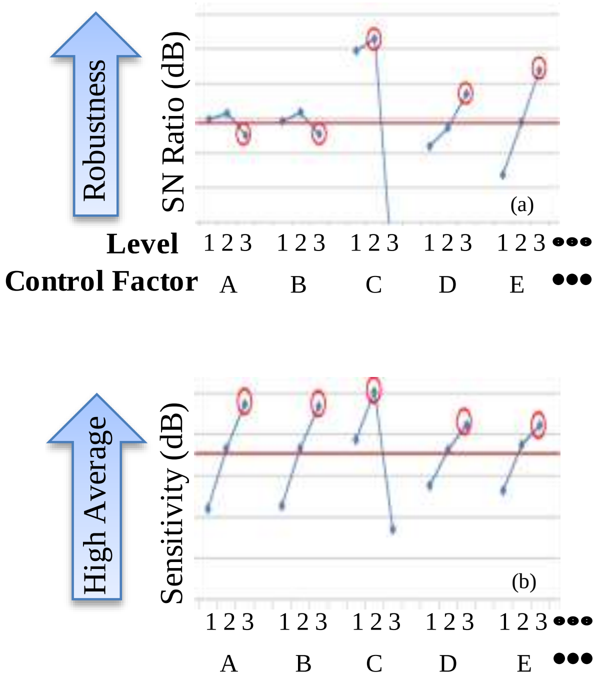

Figure 6. Graphs of Factorial Effects. Control Factors are same as Figure 4

thickness and the capacitance of the MIM capacitors. These parameters directly affect the RF characteristics. We assigned those 10 factors of manufacturing noise factors to the L36 orthogonal array with 3 levels of variation (minimum, average, maximum). Next, we chose 17 factors as the control factors including the line width, length, and area of the MIM capacitors. Then we assigned them to an L54 orthogonal array with 3 levels. In total, we carried out 1994 combinations of calculations, reading 27 factors (17 control factors + 10 noise factors) using an L54xL36 array into the simulator. Figure 6 shows the graphs of Factorial Effects for the simulation result. Using this figure, we optimized by two-step design. First we chose the level and the factors to increase the SN ratio as shown in Figure 6 (a).

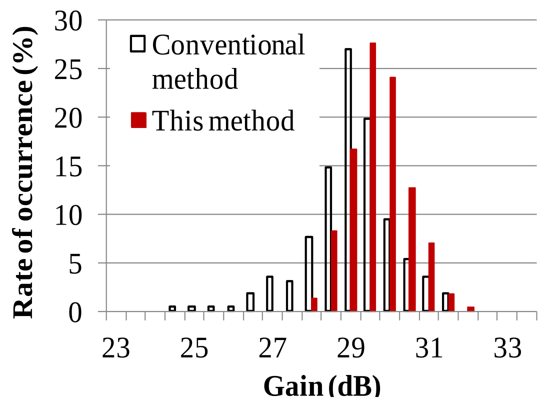

Figure 7. Comparison of the linear gain distribution (Actual measurement)

Type	Conventional method	This method	Δ
SN (dB)	28.4	32.1	3.7
Ave. (dB)	28.8	29.5	0.7
σ (dB)	1.10	0.73	-0.36 (-33%)

Figure 8. Comparison of the variation of the linear gain in the actual measurement (The signal to noise ratio, average and sigma)

Next, we increased the average value in the factors in the small variation of the SN ratio as shown in Figure 6 (b).

To verify the effectiveness of this new design approach, we actually manufactured both MMICs designed with the conventional method and this new method optimizing the linear gain performance. In the manufacturing process, we had intentionally included the variation in the noise factors. Figures 7 and 8 show the results of the Gain characteristics. In this way, we succeeded in improving the SN ratio by +3.7 dB, reducing the standard deviation by -33%, and increasing the average value of +0.7 dB.

Furthermore, we had applied another design iteration optimizing the power performance, which is a nonlinear characteristic. Simulation results successfully indicated a tighter distribution and higher average value of the Psat, as shown in Figures 9 and 10.

CONCLUSIONS

We report on the method and the effect of improvement of the characteristic variation of the MMIC designs using the Taguchi Method. If this technique is used in the microwave circuit design, it is possible to easily and visually attain optimization in a design phase without depending on experience and intuition. We succeeded in demonstrating the improvement effect by measuring it in the actual MMIC production.

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ACRONYMS

SN ratio: Signal-to-Noise ratio
MMIC: Monolithic microwave integrated circuit

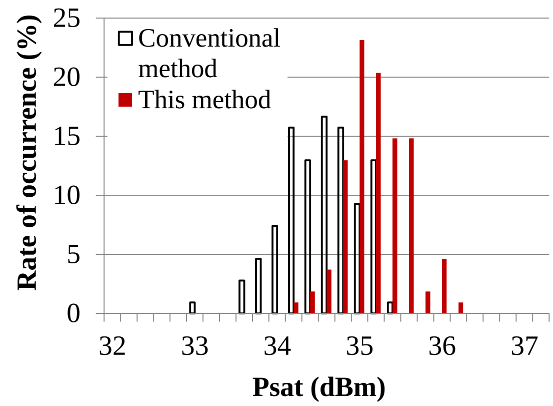

Figure 9. Comparison of the Psat in distribution (Simulation)

	Conventional method	This method	Δ
SN (dB)	37.7	39.5	1.8
Ave. (dB)	34.5	35.2	0.7
σ (dB)	0.45	0.37	-0.08 (-18%)

Figure 10. Comparison of the variation of the Psat in the Simulation (The signal to noise ratio, average and sigma)