International Journal of Applied Engineering Research
ISSN 0973-4562 Volume 10, Number 10 (2015) pp. 26149-26163

http://www.ripublication.com

Analysis of Power and Gain using Standard L_9 (3^4) and L_{27} (3^{13}) for Class AB Amplifier

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Abstract

High demand of excellent gain and low power in an amplifier has increased research in optimization method in the amplifier. In this paper, Taguchi method has been applied to optimize power dissipation and gain in a two-stage class AB amplifiers. This method is based on statistical approach which used specified standard orthogonal array and the characteristic signal to noise (S/N) ratio to analyze the improvement of gain and power dissipation quality. Two orthogonal arrays have been chosen based on standard L_9 (3^4) and standard L_{27} (3^{13}). Analyses of two orthogonal arrays have been applied in this paper to compare the produced S/N ratio. The simulations have been verified using Cadence software. From the simulations, it is found that both standards produced similar gain though different orthogonal arrays are used. The produced gain has been increased from 33.23 dB to 36.08 dB and power dissipation has been reduced from 0.7287 mW to 0.6805 mW by using Taguchi's method.

Keyword- Taguchi, power, gain, op-amp, optimize

I. INTRODUCTION

Currently, optimization techniques have been chosen to optimize required parameters and to obtain desired output. By applying optimization technique, a lot of consumed time in research can be reduced and it also not involves with costing impact to be implemented. A lot of methods have been used in optimizing parameters in a circuit such as Analog Migration for ICs with Genetic Optimization (AMIGO) [1], geometric

programming [2], gain-boosted op-amp [3], systematic design procedure [4] and unspecified method [5]. Common optimization methods require systematic parameter and complicated equations involved in the optimization method. Meanwhile, unspecified method required a lot of time consumption due to need of choosing the best selection parameters in order to produce the excellent output. Thus, Taguchi method which it based on statistical approach is introduced in this paper due to it offers easier optimization technique with minimum time used. This method has been widely applied in factors determination in diesel engine [6], end milling operation [7], refrigerated gas plan [8], radiofrequency identification [9] and etc. In amplifier circuit, this method has been applied on RF amplifier [10], current mirror amplifier [11] and two-stage op-amp [12].

Class AB amplifier has been chosen in this work due to it offers good gain and excellent power and linearity [13]. Two outputs have been aimed to be optimized which are gain and power dissipation in the amplifier. In this paper, two standards which known as standard L_9 and standard L_{27} in Taguchi method will be applied to optimize the selected outputs. Corresponding S/N ratio produced by both standards will be analysed and compared.

II. METHODOLOGY

In methodology part, architecture of class AB amplifier, optimization of power and gain using Taguchi method, analysis of Taguchi method and comparison between both standards will be discussed in details.

A. Architecture of Class AB amplifier

Fig. 1 shows schematic of class AB amplifier used in this paper. Architecture of this op-amp is constructed base on two-stage op-amp configuration. It consists of six P-MOS types and six N-MOS type of CMOS transistors. Table I shows the value of W/L ratio proposed by Khumsat *et. al*. All the transistors are constructed using 0.18 µm technology by CEDEC and Cadence software is used to construct the schematic circuit and verify the results.

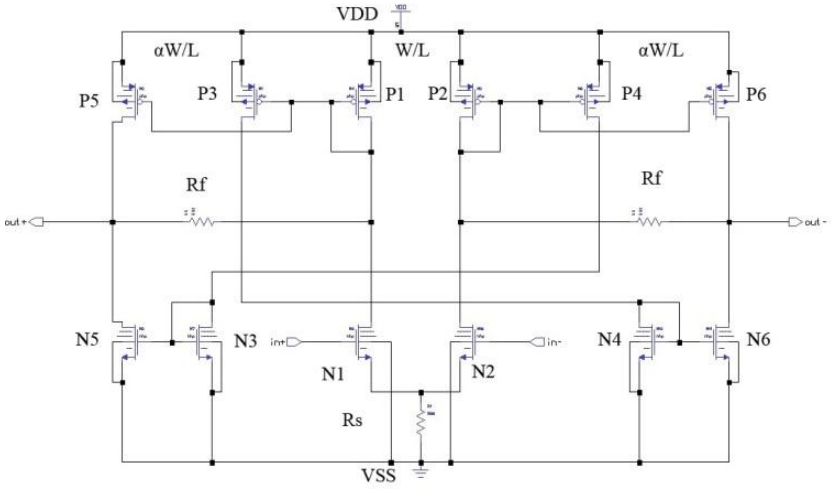

Fig. 1. Schematic of class AB amplifier [5]

TABLE I Value Of W/L Ratio [14]

Transistors	W/L (µm/µm)
N1-N2	1.5/0.18
P1-P2	10/0.5
P3-P6	25/0.5
N3-N6	5/0.5

Based on the Fig. 1, the transimpedance gain (R_m) can be calculated as follow [14]:

$$R_m = -\left(\frac{R_f A_i - R_{in}}{1 + A_i} \right) \tag{1}$$

Where R_m is transimpedance gain, R_f is shunt feedback, A_i is current gain and R_{in} is input impedance. Where R_{in} and A_i act as the input resistance and the current gain of the current in this amplifier. When $A_i >> 1$, then $R_m = -R_f$. Transconductance gain, G_m part is as the first stage of the op-amp. The transconductance gain, G_m is given as [14]:

$$G_m = \frac{g_m}{1 + g_m R_s + s R_s C_{gs}} \tag{2}$$

Where g_m is transconductance at N1, C_{gs} is gate source capacitance at N2 and R_s is source resistor. For current gain (A_i), it can be analysed as follows [14]:

$$A_i = \frac{g_{mx}}{(g_{mi} + sC_x)} \left(1 + \frac{g_{my}}{(g_{my} + sC_y)} \right) \tag{3}$$

Where g_{mx} is transconductance at P1-P2, g_{my} is transconductance at P3-P6, g_{mi} is transconductance at N3-N6, C_x is equivalent total capacitance at gate P1 and P2 and C_y is equivalent total capacitance at gate N3 and N4. The equation for input resistance R_{in} is obtained by [14]:

$$R_{in} = \frac{1}{g_{mi} + sC_x} \tag{4}$$

Where g_{mi} is transconductance at N3-N6 and C_x is equivalent total capacitance at gate P1 and P2. A small-signal transimpedance gain, R_m could be obtained to be by substituting the (3) and (4). It can be expressed as follows [14]:

$$R_m = -\frac{\alpha\left[2R_f\frac{1}{g_{mx}} + s\frac{C_y}{g_{my}}\left(R_f - \frac{1}{g_{mx}}\right)\right]}{2\left[1+\alpha+s\left(\frac{C_y}{g_{my}}\left(1+\frac{\alpha}{2}\right)+\frac{C_x}{g_{mi}}\right)+s^2\frac{C_xC_y}{g_{mi}g_{my}}\right]}, \alpha = 5 \quad (5)$$

Where R_f is shunt feedback, C_y is equivalent total capacitance at gate N3 and N4, C_x is equivalent total capacitance at gate P1 and P2, g_{my} is transconductance at P3-P6, g_{mx} is transconductance at P1-P2 and g_{mi} is transconductance at N3-N6. The value of feedback resistor, R_f is used to select a voltage gain range and meanwhile the source resistor, R_s is used to vary the amplifier gain [5].

B. ***Optimization of Power and Gain using Taguchi Method***

Taguchi defines the quality of a product, in terms of the loss imparted by the product to the society from the time the product is shipped to the customer. Taguchi method offers simple and systematic approach to optimize design for performance, quality and cost [15]. Taguchi's approach is totally based on statistical design of experiments and by applying this technique, the time required for experimental design can be reduced. By investigating the effects of multiple factors, the individual factor which gives more or less influence impact on the performance can be determined [16].
Two major robust tools used in Taguchi method are signal to noise ratio which measures quality with emphasis on variation and second is orthogonal arrays which accommodate many design factors simultaneously. The S/N ratio characteristics are divided into three categories as following [15]:

1) Nominal is the best characteristics,

$$S/N = 10\log\frac{\bar{y}}{s_y^2} \quad (6)$$

2) Smaller the better characteristics,

$$S/N = -10\log\frac{1}{n}\sum y^2 \quad (7)$$

3) Larger the better characteristics,

$$S/N = -10\log\frac{1}{n}\left(\sum\frac{1}{y^2}\right) \quad (8)$$

Where $\bar{y}$ is average of observed data, s_y^2 is variance of y, n is number of observations and y is observed data. The combination that produced highest S/N ratio in the characteristics will be chosen as best combination. In this paper, Taguchi method will be applied in the circuit by optimizing the value of width and length of the transistors, in order to achieve low power dissipation and higher gain. Therefore, equation (7) will be applied to the power dissipation to achieve smaller power

dissipation and highest S/N ratio value can be achieved. In order to achieve high gain, equation (8) will be used to achieve larger gain and highest S/N ratio. Value of *y* will be varied according to the value that produced from simulation. Two types of orthogonal arrays will be used which are standard L_9 (3^4) and standard L_{27} (3^{13}).

III. RESULTS AND DISCUSSION

Fig. 2 shows the schematic circuit was constructed using Cadence software. The setting parameters to run this simulation are shown in Table II.

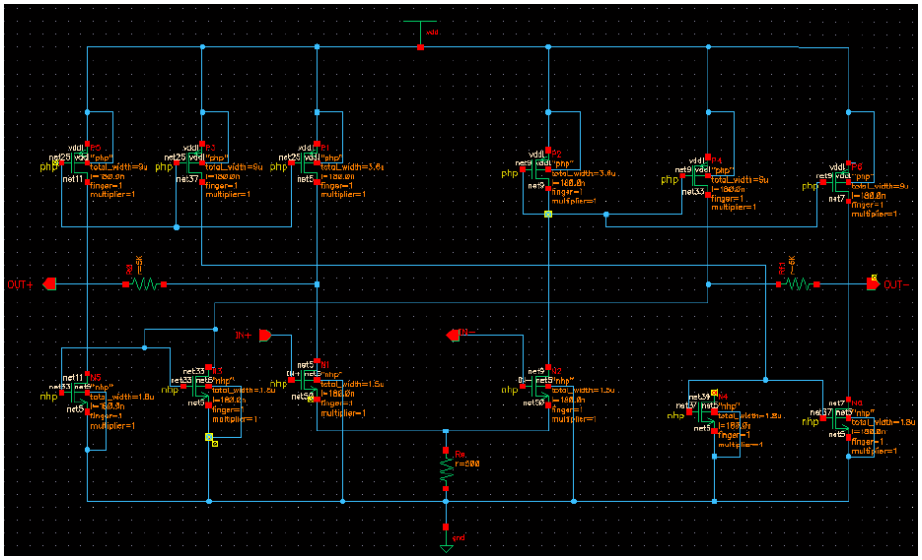

Fig. 2. Topology of class AB amplifier in Cadence

TABLE II SIMULATION PARAMETERS

Parameters	Value
Vin+	1V
Vin-	-1V
Frequency	1 MHz
Vdd	1.8V
Vdc	1V
Acm	1mA

A. Analysis of gain by different value of R_s and R_f

This op-amp also known as variable gain amplifier (VGA), where value of gain produced by this op-amp can be adjusted by changing the value of R_s and R_f in the circuit. R_s is a source resistor and R_f is a feedback resistors. R_s resistor is connected between transistor N1 and N2, which the both resistors are connected with the input voltage. Meanwhile, R_f is connected at output side. Adjustment of R_s value will give

effect on noise and R_f value is used to maintain the value of gain. Table III shows the value of gain produced when R_s and R_f are varied. The gain produced is in the range of 1.193 dB until 33.23 dB for 1 MHz frequency.

TABLE III Gain Response By Different Value Of R_s And R_f

R_s	R_f	Gain
500	500k	29.61
	150k	25.77
	50k	19.6
	15k	10.81
5k	500k	33.23
	150k	25.2
	50k	16.54
	15k	6.513
15k	500k	29.91
	150k	20.64
	50k	11.51
	15k	1.193

From these analyses, the combination value of R_s and R_f that produced highest gain will be chosen and it will be used as fixed parameters in the circuit. From Table III, it is found that when R_s is 5kΩ and R_f is 500kΩ, it will produced the highest gain which is 33.32 dB. Thus, this combination will be used in the next analysis which is to optimize power and gain using Taguchi's method. Fig. 3 shows the frequency response produced from this op-amp. It showed that the produced gain is 33.23 dB. Power dissipation produced by using R_s = 5kΩ and R_f = 500kΩ is 0.7287mW.

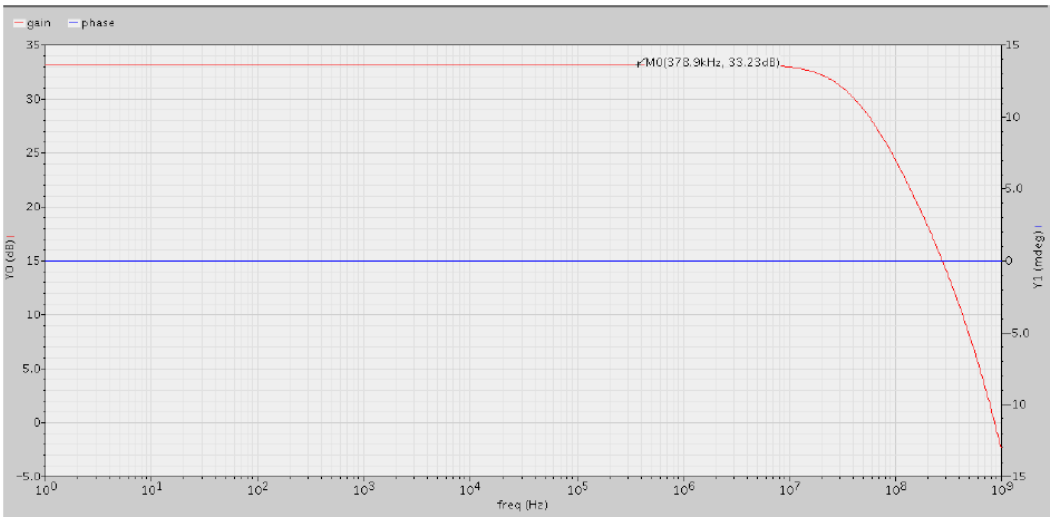

Fig. 3. Frequency response of proposed op-amp

B. ***Analysis of Taguchi method on Gain***

Before optimization can be started, we need to choose the control factors. The control factors are decided based on the value of W/L ratio that can affect the value of gain and power in the op-amp. Thus, three transistors will be used as control factors which are transistors at P1, N3 and N5. These transistors are selected based on equation (3), (4) and (5) due to these transistors will affect the value of gain. Table IV shows the values of W/L ratio that have been used in previous research [10]. The proposed values of control factors used in this Taguchi method are shown in Table V. Next, the op-amp will be simulated according to the sequence of standard L_9 (3^4) and standard L_{27} (3^{13}). The sequence of orthogonal array of standard L_9 (3^4) and standard L_{27} (3^{13}) are attached in the Appendix.

TABLE IV Selection Of Control Factors

Transistors	W/L (um/um)	Ratio
P1-P2	10/0.5	20
N3-N4	5/0.5	10
N5-N6	5/0.5	10

TABLE V Values of Control Factors

Control factor		Level		
		1	2	3
A	P1-P2	3.6/0.18	19.8/0.99	13.6/0.68
B	N3-N4	9/0.18	49.5/0.99	34/0.68
C	N5-N6	1.8/0.18	9.9/0.99	6.8/0.68

Both of standards L_9 (3^4) and standard L_{27} (3^{13}) used three control factors, thus values in Table V will be applied for both standards. The different of standard L_9 (3^4) and standard L_{27} (3^{13}) is standard L_9 (3^4) produced nine outputs of S/N ratio and standard L_{27} (3^{13}) produced 27 outputs of S/N ratio. Table VI and Table VII show the designation of both standards respectively.

TABLE VI Designation and Control Factors For Standard L_9 (3^4)

Experiment no.	Designation	Control factors		
		A	B	C
1	A1 B1 C1	3.6/0.18	9/0.18	1.8/0.18
2	A1 B2 C2	3.6/0.18	49.5/0.99	9.9/0.99
3	A1 B3 C3	3.6/0.18	34/0.68	6.8/0.68
4	A2 B1 C2	19.8/0.99	9/0.18	9.9/0.99
5	A2 B2 C3	19.8/0.99	49.5/0.99	6.8/0.68
6	A2 B3 C1	19.8/0.99	34/0.68	1.8/0.18

7	A3 B1 C3	13.6/0.68	9/0.18	6.8/0.68
8	A3 B2 C1	13.6/0.68	49.5/0.99	1.8/0.18
9	A3 B3 C2	13.6/0.68	34/0.68	9.9/0.99

Table VII shows value of power dissipation and their corresponding S/N ratio produced from simulation using standard L_9 (3^4). It is found that experiment no. 5 has produced highest S/N ratio which is 31.6717 dB and lowest power dissipation which is 0.6805 mW. Meanwhile, Table IX shows value of gain and their corresponding S/N ratio. Based on Table IX, experiment no. 4 has produced highest gain which is 36.08 dB and highest S/N ratio which is 31.1453 dB. Due to the higher gain is preferred in this work rather than the lowest power, thus the best combination to improve the power dissipation and gain is chosen based on experiment no. 4 which is combination of A2 B1 C2. The value of W/L transistor at P1, N3 and N5 are 19.8/0.99, 9/0.18, and 9.9/0.99 respectively.

TABLE VII Power Dissipation Produced In Standard L_9 (3^4)

Experiment No.	Designation	Power (mW)	S/N ratio (dB)
1	A1 B1 C1	0.6891	31.6172
2	A1 B2 C2	0.6869	31.6311
3	A1 B3 C3	0.6905	31.6084
4	A2 B1 C2	0.6842	31.6482
5	A2 B2 C3	0.6805	31.6717
6	A2 B3 C1	0.6817	31.6641
7	A3 B1 C3	0.7244	31.4002
8	A3 B2 C1	0.7219	31.4152
9	A3 B3 C2	0.7212	31.4194

TABLE IX Gain Produced In Standard L_9 (3^4)

Experiment No.	Designation	Gain (dB)	S/N ratio (dB)
1	A1 B1 C1	27.14	28.6722
2	A1 B2 C2	33.34	30.4593
3	A1 B3 C3	32.20	30.1571
4	A2 B1 C2	36.08	31.1453
5	A2 B2 C3	33.77	30.5706
6	A2 B3 C1	25.92	28.2727
7	A3 B1 C3	35.61	31.0314
8	A3 B2 C1	25.66	28.1851
9	A3 B3 C2	34.06	30.6449

Table X shows the designation and control factors for standard L_{27} (3^{13}). Power dissipation and their corresponding S/N ratio by using standard L_{27} (3^{13}) is

shown in Table XI. Based on the value of corresponding S/N ratio, it showed that experiment no. 14 has produced highest S/N ratio which is 31.6717 dB and lowest power dissipation which is 0.6805 mW.

TABLE X Designation And Control Factors For Standard L_{27} (3^{13})

Experiment no.	Designation	Control factors		
		A	B	C
1	A1 B1 C1	3.6/0.18	9/0.18	1.8/0.18
2	A1 B2 C2	3.6/0.18	49.5/0.99	9.9/0.99
3	A1 B3 C3	3.6/0.18	34/0.68	6.8/0.68
4	A2 B1 C1	19.8/0.99	9/0.18	1.8/0.18
5	A2 B2 C2	19.8/0.99	49.5/0.99	9.9/0.99
6	A2 B3 C3	19.8/0.99	34/0.68	6.8/0.68
7	A3 B1 C1	13.6/0.68	9/0.18	1.8/0.18
8	A3 B2 C2	13.6/0.68	49.5/0.99	9.9/0.99
9	A3 B3 C3	13.6/0.68	34/0.68	6.8/0.68
10	A1 B1 C2	3.6/0.18	9/0.18	9.9/0.99
11	A1 B2 C3	3.6/0.18	49.5/0.99	6.8/0.68
12	A1 B3 C1	3.6/0.18	34/0.68	1.8/0.18
13	A2 B1 C2	19.8/0.99	9/0.18	9.9/0.99
14	A2 B2 C3	19.8/0.99	49.5/0.99	6.8/0.68
15	A2 B3 C1	19.8/0.99	34/0.68	1.8/0.18
16	A3 B1 C2	13.6/0.68	9/0.18	9.9/0.99
17	A3 B2 C3	13.6/0.68	49.5/0.99	6.8/0.68
18	A3 B3 C1	13.6/0.68	34/0.68	1.8/0.18
19	A1 B1 C3	3.6/0.18	9/0.18	6.8/0.68
20	A1 B2 C1	3.6/0.18	49.5/0.99	1.8/0.18
21	A1 B3 C2	3.6/0.18	34/0.68	9.9/0.99
22	A2 B1 C3	19.8/0.99	9/0.18	6.8/0.68
23	A2 B2 C1	19.8/0.99	49.5/0.99	1.8/0.18
24	A2 B3 C2	19.8/0.99	34/0.68	9.9/0.99
25	A3 B1 C3	13.6/0.68	9/0.18	6.8/0.68
26	A3 B2 C1	13.6/0.68	49.5/0.99	1.8/0.18
27	A3 B3 C2	13.6/0.68	34/0.68	9.9/0.99

TABLE XI Power Dissipation Using Standard L_{27} (3^{13})

Experiment No.	Designation	Power (mW)	S/N ratio (dB)
1	A1 B1 C1	0.6891	31.6172
2	A1 B2 C2	0.6859	31.6374
3	A1 B3 C3	0.6905	31.6084
4	A2 B1 C1	0.6843	31.6475
5	A2 B2 C2	0.6806	31.6711

6	A2 B3 C3	0.6857	31.6387
7	A3 B1 C1	0.7244	31.4002
8	A3 B2 C2	0.7211	31.4200
9	A3 B3 C3	0.7264	31.3882
10	A1 B1 C2	0.6889	31.6184
11	A1 B2 C3	0.6859	31.6374
12	A1 B3 C1	0.6869	31.6311
13	A2 B1 C2	0.6842	31.6482
14	A2 B2 C3	0.6805	31.6717
15	A2 B3 C1	0.6817	31.6641
16	A3 B1 C2	0.7245	31.3996
17	A3 B2 C3	0.7233	31.4068
18	A3 B3 C1	0.7219	31.4152
19	A1 B1 C3	0.6888	31.6191
20	A1 B2 C1	0.6869	31.6311
21	A1 B3 C2	0.6860	31.6368
22	A2 B1 C3	0.6841	31.6488
23	A2 B2 C1	0.6817	31.6641
24	A2 B3 C2	0.6807	31.6704
25	A3 B1 C3	0.7244	31.4002
26	A3 B2 C1	0.7219	31.4152
27	A3 B3 C2	0.7212	31.4194

Table XII shows gain value and their corresponding S/N ratio produced by using standard L_{27} (3^{13}). It is found that experiment no. 13 has produced highest gain which is 36.08 dB and its corresponding S/N ratio is 31.1453 dB. Due to the highest gain is more preferred in this case, thus experiment no. 14 will be chosen as best combination produced optimal power and gain compared to the experiment no. 13. Experiment 14 is combination from A2 B2 C3 which based on W/L transistor at P1 is 19.8/0.99, W/L transistor at P3 is 49.5/0.99 and W/L transistor at N3 is 6.8/0.68.

TABLE XII Gain And Corresponding S/N Ratio For Standard L_{27} (3^{13})

Experiment No.	Designation	Gain	S/N ratio
1	A1 B1 C1	27.14	28.6722
2	A1 B2 C2	33.34	30.4593
3	A1 B3 C3	32.20	30.1571
4	A2 B1 C1	28.35	29.0511
5	A2 B2 C2	34.07	30.6474
6	A2 B3 C3	32.99	30.3676
7	A3 B1 C1	28.2	29.0050
8	A3 B2 C2	33.94	30.6142
9	A3 B3 C3	32.86	30.3334

10	A1 B1 C2	35.17	30.9234
11	A1 B2 C3	33.02	30.3755
12	A1 B3 C1	25.00	27.9588
13	A2 B1 C2	36.08	31.1453
14	A2 B2 C3	33.77	30.5706
15	A2 B3 C1	25.92	28.2727
16	A3 B1 C2	35.92	31.1067
17	A3 B2 C3	33.58	30.5216
18	A3 B3 C1	25.82	28.2391
19	A1 B1 C3	34.85	30.8441
20	A1 B2 C1	24.86	27.9100
21	A1 B3 C2	33.45	30.4879
22	A2 B1 C3	35.78	31.0728
23	A2 B2 C1	25.77	28.2223
24	A2 B3 C2	34.19	30.6780
25	A3 B1 C3	35.61	31.0314
26	A3 B2 C1	25.66	28.1851
27	A3 B3 C2	34.06	30.6449

C. Comparison on standard L_9 (3^4) with standard L_{27} (3^{13})

Based on the analyses that have been done, it is found that the value of highest gain and lowest power dissipation produced by both standards are same. However, the combinations of control factors are different for both standards. Table XIII shows comparison between standard L_9 (3^4) and L_{27} (3^{13}). It is found that control factor A used same value of W/L transistor, meanwhile control factor B and C did not use same value of W/L transistors in standard L_9 (3^4) and L_{27} (3^{13})..

TABLE XIII Comparison Between Standard L_9 (3^4) And L_{27} (3^{13})

Standard	Optimal combination	Control factors		
		A	B	C
L_9 (3^4)	A2 B1 C2	19.8/0.99	9/0.18	9.9/0.99
L_{27} (3^{13})	A2 B2 C3	19.8/0.99	49.5/0.99	6.8/0.68

Fig. 4 shows the frequency response produced by Taguchi's approach. It showed that the highest gain produced by using Taguchi's method is 36.08 dB. It can be concluded that both combinations produced by standard L_9 (3^4) and L_{27} (3^{13}) can be used as optimal combination of power and gain in class AB amplifier.

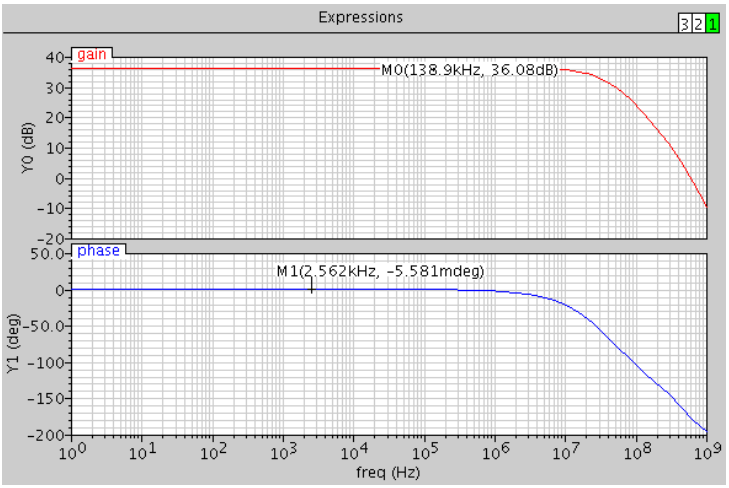

Fig.4. Gain and phase produced by Taguchi's approach

IV. CONCLUSION

By using Taguchi's approach as an optimization method in class AB amplifier, it showed that Taguchi method is a simple, systematic, and efficient method in optimization technique. Implementation of Taguchi method in this amplifier has reduced the power dissipation from 0.7287 mW to 0.6842 mW and it also has increased gain from 33.23 dB to 36.08 dB. This research has proved that any standards in Taguchi method can be chosen for optimization and both standards will produce similar optimum output with different control factors and designation.

D. Comparison between previous researches

This work also has been compared with previous researches that used similar configuration of op-amp. Table XIV shows the comparison in gain performances. From the comparison, it showed that Taguchi's method has increased the value of gain in the op-amp. Thus, this study also showed that Taguchi's method can be applied in any field of engineering to optimize any parameters.

TABLE XIV Comparison in Gain Performance

Parameters	This work	Circuit in [14]	Circuit in [5]
Technology	CEDEC 0.18 µm CMOS	SPECTRE 0.18 µm CMOS	CEDEC 0.18 µm CMOS
Optimization method	Taguchi's method	Not applicable	Unspecified method
Gain	36.08 dB	25 dB	26 dB

ACKNOWLEDGMENT

The author would like to thank Universiti Teknikal Malaysia Melaka, Malaysia (UTeM) for funding this project under Short Term Grant.

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Appendix

Appendix A1 Orthogonal array L_9

Experiment no.	Control factors		
	A	**B**	**C**
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Appendix A2 Orthogonal array L_9

Experiment no.	Control factors		
	A	**B**	**C**
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	1
5	2	2	2
6	2	3	3
7	3	1	1
8	3	2	2
9	3	3	3
10	1	1	2
11	1	2	3
12	1	3	1
13	2	1	2
14	2	2	3
15	2	3	1
16	3	1	2
17	3	2	3
18	3	3	1
19	1	1	3
20	1	2	1
21	1	3	2
22	2	1	3
23	2	2	1
24	2	3	2
25	3	1	3
26	3	2	1
27	3	3	2