Robust Optimization of PCB Differential-Via for Signal Integrity

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***Abstract*—This paper describe a electromagnetic optimization technique using Taguchi's method. Taguchi's method was developed on the basis of the orthogonal array (OA) concept, which offers systematic and efficient characteristics. In manufacturing, the dielectric constant of High-speed PCB's dielectric material is uncontrollable factor. The paper carries out a comprehensive study of the impacts of the different dielectric constant in various differential-via design parameters on signal integrity (SI) using DOE of Taguchi method. To optimize the differential-via's parameters so that there is small effect on SI in different dielectric material.**

Keywords*—*Signal Integrity; Robust Optimization; Design of Experiments(DOE); HFSS

I. INTRODUCTION

In this paper, We mainly analysis under different structure parameters and dielectric constant of the tiny changes impact on differential-via's signal integrity. And we compare the S-parameters in different cases and a lot of simulations have been done to demonstrate how those parameters affect the signal integrity with the help of a full-wave 3-D electromagnetic solver (HFSS). In 1980, Taguchi's introduction of robust design to several major American industries resulted in significant quality improvements in product and manufacturing process design. His parameter design, in a narrow sense, where the levels (values) of design variables (control factors) minimize the effect of noise on the product's quality, must be determined to find the optimum levels. This paper also use the Taguchi method to optimize the differential-via's parameters so that there is small effect on Signal Integrity in different dielectric constant.

A. Signal Integrity

"Signal Integrity (SI) ensures that a signal is moved from point A to point B with sufficient quality or integrity to allow effective communication" [1]. Now, as technology innovation marches forward, new kinds of devices, media formats, and large inexpensive storage are converging. They require significantly more bus bandwidth and transfer rate to maintain the interactive experience users have come to expect. Signal Integrity analysis becomes important to ensure reliable high-speed data transmission. In this paper, we use the differential to common mode conversion (S_{dc}dB: Driver is common mode and receiver is differential) as the main performance of differential-via's signal integrity.

B. Design of Experiments(DOE)

Design of Experiments is a systematic method for determining the effect of factors and their possible interactions in a design or a process towards achieving a particular output of the quality characteristic(s)[2]. DOE is used to ensure the value of the selected output parameter (which is called Quality Parameters) within defined range, when the system has unwanted and uncontrollable design variations. Thus, DOE is a method to design a system in a robust way as well as meeting the system output requirements. The 'treatments' are the well-defined procedures or experiments to examine a system for its output characteristics. An 'interaction' is the variation among the differences between means for different levels of one factor over different levels of the other factor.

C. Taguchi method

Taguchi method is a methodology based on orthogonal arrays (OAs) concept, which effectively reduces the number of test iterations required in an optimization process [3]. Taguchi optimization technique is predominantly used in industrial engineering, in which the experiments are planned for designing of a product efficiently and reliably. Based on these experiments, the effects of various factors on design are calculated. Therefore, by controlling dominant factor, product is optimized to achieve better quality. This study shows that the method can quickly converge to the desired design since it takes less computational resource. Most important of all, Taguchi method is easy and straightforward to implement.

The orthogonal array, which has a profound background from statistics [4], plays an essential role in the method. The selection of an orthogonal array depends on the input parameters of an optimization problem.

D. Orthogonal array

A matrix experiment consists of a set of experiments. Each experiment is performed by changing the setting of the various product or process parameters which has to study. After conducting matrix experiments, the data from all experiments in the set taken together is analyzed to determine the effects of various parameters. Matrix experiments are conducted using special matrices, called "orthogonal arrays" [5]. Number of arrays was designed. Every array is directed to a special type of experimental situation. The title orthogonal expresses that the array is balanced. The word balance expresses that every column is balanced within itself and that any two columns in the arrays are also balanced. That means, at first, that within a column, there are an equal number of levels. At second, that means that any two columns in the arrays are also balanced. This balance between any two columns assures that all possible factor combinations exist in equal numbers [6].

E. Robust Optimization

Robust optimization means to optimize a design in such a way that it will certainly work according to the specifications for which it is desired to work. Taguchi Methods are used for general Robust Optimization. There are various other methods also that perform Risk Analysis for robust optimization [7].The approach used in the paper is to make the robust optimization of differential-via's parameters so that there is small effect on signal integrity in different dielectric constant.

II. MOLDING HFSS

The differential-vias has been designed in 3D full wave modeling (HFSS). The boards are 5mil thick, the layers are 1.2mil thick and the high speed trace is 5mil wide as shown in the Figure 1 and Figure 2.

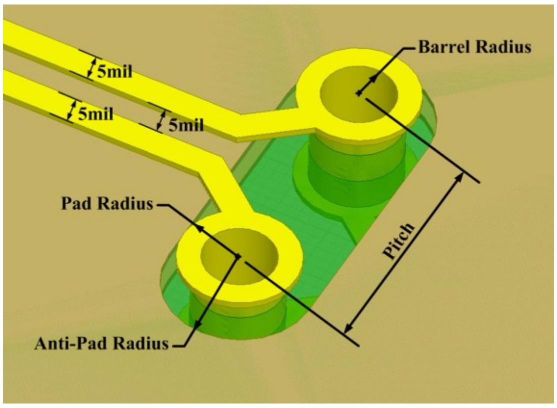

Fig. 1. HFSS Differential-via Modeling

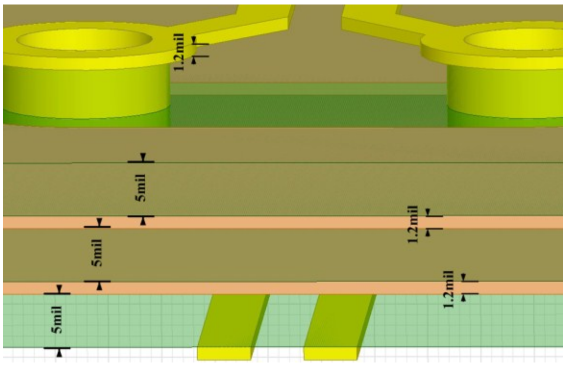

Fig. 2. Differential-via Parameters

In this DOE, we used three dielectric materials. Their dielectric constants respectively are ε_1=4, ε_2=4.4 and ε_3=4.6. Their loss tangent are 0.02. The physical dimensions considered as variables into the experiments were the next:

R1=Barrel Radius;

R2=Pad Radius;

R3=Anti-Pad Radius;

P=Pitch(as shown in the Figure 1);

In our case the random variables or factors are 4 and the levels are 3, so the Taguchi Array of $L_9(3^4)$ is used. The experiments or the orthogonal simulations performed are planned according to this array. The $L_9(3^4)$ Taguchi Array is used from [6]. The factor selected and level values are illustrated in Table I. Table II shows the values of orthogonal array selected $L_9(3^4)$

TABLE I. FACTOR AND LEVEL SELECTION

Factors	Level 1	Level 2	Level 3
Barrel Radius(R1)	5mil	6.5mil	8mil
Pad Radius(R2)	9mil	10.5mil	12mil
Anti-pad Radius(R3)	13mil	14.5mil	16mil
Pitch(P)	34mil	38mil	42mil

TABLE II. VALUES OF ORTHOGNAL ARRAY

Experiment	R1	R2	R3	P
Case1	1	1	1	1
Case2	1	2	2	2
Case3	1	3	3	3
Case4	2	1	2	3
Case5	2	2	3	1
Case6	2	3	1	2
Case7	3	1	3	2
Case8	3	2	1	3
Case9	3	3	2	1

III. SIMULATION

In this subsection, the modeling of multimode S-Parameters has been obtained after simulating each case in HFSS.

The differential-to-common mode S-parameters($S_{dc}21$), where the energy is being transmitted in the odd mode and received in the even mode. Used the dielectric materials which dielectric constants is ε_2=4.4, the $S_{dc}21$ results are shown in Figure 3.

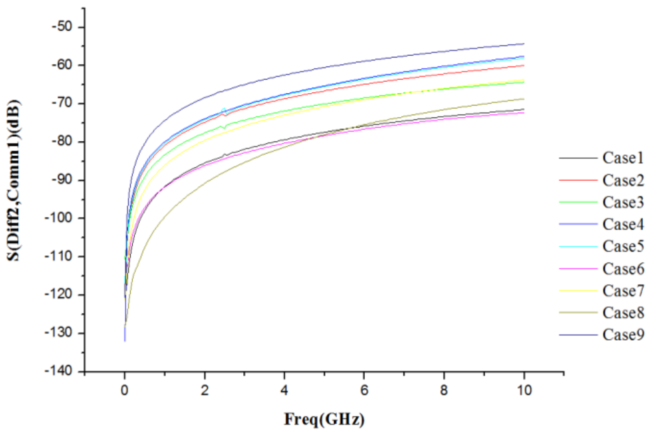

Fig. 3. The Differential-to-common mode S-parameters ($S_{dc}21dB$)

As lower curves as better signal quality can be expected. In Figure 3, it can be observed that cases Case1, Case6 and Case8 have the lowest values as the frequency increases. The cases showing the highest was Case9.

When using the same method, we also can get the differential-to-common mode S-parameters($S_{dc}21$) in different dielectric constant(ε_1=4, ε_3=4.6).

Using the simulation results, we calculated average S-parameters by Eq. (1). The outputs are Y_1, Y_2 and Y_3, as shown in Table III.

$$Y_n = \overline{S_{dc}21}_{CaseN}(dB) \qquad (1)$$

TABLE III. SIMULATION RESULTS OF EXPERIMENT

Simulation	Y1(ε1)dB	Y2(ε2)dB	Y3(ε3)dB
Case1	-72.39	-80.17	-75.52
Case2	-70.16	-69.29	-71.33
Case3	-69.53	-72.54	-66.53
Case4	-66.74	-67.88	-64.3
Case5	-74.63	-68.13	-72.41
Case6	-80.75	-80.75	-68.07
Case7	-69.86	-73.58	-75.7
Case8	-76.8	-81.88	-86.52
Case9	-68.77	-63.18	-64.16

$$\mu = \frac{1}{3}\sum_{i=1}^{n} Y_n(dB) \qquad (2)$$

$$\sigma^2 = \frac{1}{3}\sum_{i=1}^{3}\left(Y_n - \mu\right)^2 \qquad (3)$$

Using the Eq. 2 and Eq. 3, we calculate the mean(μ) and variance(σ^2) as shown in Table IV.

TABLE IV. CALCULATED RESULTS

Simulation	μ(dB)	σ^2
Case1	-76.02	15.3
Case2	-70.26	1.06
Case3	-69.53	9.03
Case4	-66.3	3.36
Case5	-71.72	10.9
Case6	-76.52	53.63
Case7	-73.05	8.75
Case8	-81.73	23.63
Case9	-65.37	8.88

IV. STATISTICAL ANALYSIS

The purpose of this robust optimization is select the differential-via's parameters design, in a narrow sense, where the levels of design variables (control factors) minimize the effect of different dielectric constant(un-control factor) on the differential-via's signal integrity, must be determined to find the optimum levels. The parameters are R1(Barrel Radius), R2(Pad Radius), R3(Anti-Pad Radius) and P(Pitch).

A. Analysis of Mean(μ)

The regression equation for Mean of output is stated as below:

$$\begin{aligned} Mean(\mu) &= -77.33 - 0.722R1 + 0.653R2 \\ &\quad + 3.33R3 - 0.742P \end{aligned} \qquad (4)$$

The differential-to-common mode S-parameters ($S_{dc}21$) is the smaller the better. In the Eq. (4), sensitivity coefficients for μ of R3 is the largest. So the R3 has the most significant effect on μ; the second are P and R1; the R2 is small effect.

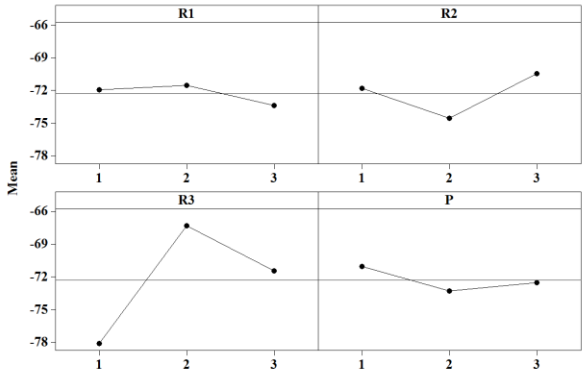

Fig. 4. Main Effects Plot(Mean of output)

In Fig. 4, the R1(Antipad Radius) and P factors have horizontal slope; therefore, they are not as significant and there is shown the independent effect of each parameter on mean of output. Use the Fig. 4, we can optimize the differential-via' signal integrity to better. The factor of R1 use the level 3. R2 use the level 2; R3 use the level 1; P use the level 2.

B. Analysis of Variance(σ^2)

The regression equation for Variance of output is stated as below:

$$\begin{aligned} Variance(\sigma^2) &= 15.93 + 2.65R1 + 7.35R2 \\ &\quad - 10.65R3 + 0.16P \end{aligned} \qquad (5)$$

The value of variance is small demonstrate the differential-via's have better robust SI in this the parameters' levels. So the R3 is also the most significant effect on μ; the second are P and R1; the R2 is small effect.

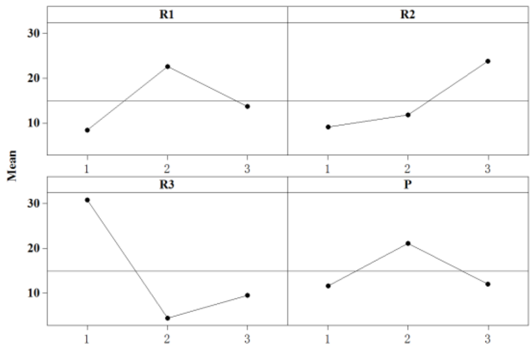

Fig. 5. Main Effects Plot(Mean of Variance)

In the Fig. 5, there is shown the independent effect of each parameter on mean of variance. So we select R1 in level 1, R2 in level 1, R3 in level 2 and P use the level 1 to optimize the differential-via's robust output.

V. OPTIMIZATION

The most significant parameter/factor can be determined by the sensitivity coefficient of the regression equation. The absolute value of the variable's coefficient is larger; the factor is more effect in the output. Main effect plot diagrams as the graphical representations of the change in performance characteristics with variation in every level, giving a pictorial view of the variation of each factor and its effect on the performance, as each factor shifts from one level to another. So the main effect plot diagrams also can determine the optimum levels of design variables. A more extreme slope indicates a more significant effect on differential-via's signal integrity. There are shown the interaction effect. So the optimized design in this case is: R1=level1; R2=level2; R3=level3; P=level3. The optimized design parameter is in TABLE V. And the optimized differential-via's mold is shown in Fig. 6 and Fig. 7. The result of simulation in different dielectric material is shown in Fig. 8. We calculate the mean(μ) is -82.28dB and variance(σ^2) is 29.17.

TABLE V. OPTIMIZED DESIGN

Parameter	Barrel Radius(R1)	Pad Radius(R2)	Anti-pad Radius(R3)	Pitch(P)
Optimized Design	5mil	10.5mil	16mil	42mil

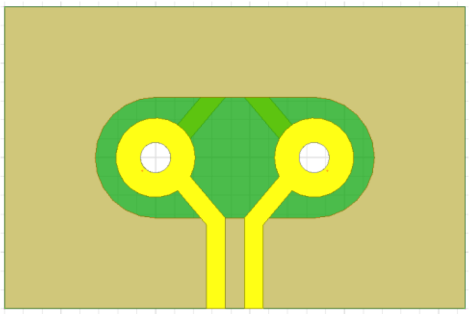

Fig. 6. The Optimized Differential-via (Top)

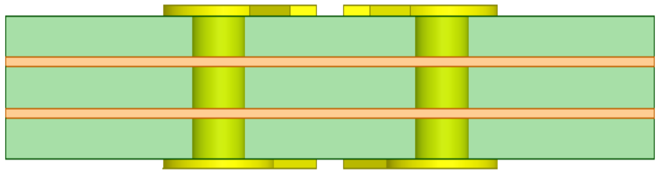

Fig. 7. The Optimized Differential-via (Front)

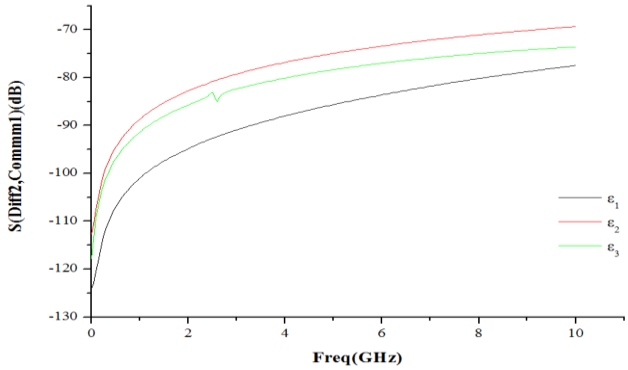

Fig. 8. The Optimized Differential-to-common mode S-parameters (S_{dc}21dB)

VI. CONCLUSIONS

In this paper, we use the Taguchi Method and HFSS to study the differential-via's signal integrity. Use the result of simulation and statistical analysis, we can find:

- The factor of the anti-pad radius is the most effect on the output.
- To set a appropriate value of anti-pad radius, it optimize the differential-via's parameters so that there is small effect on SI in different dielectric material.

In this methodology, we use no large experiments to analysis and find the best optimized parameters. There is small effect on Signal Integrity in different dielectric constant. The design engineer, early in the program, can work with PCB suppliers to achieve a balance between differential-via performance. The methodology can be used to optimize any similar system.

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