Advances in Computer Science Research, volume 89
2019 International Conference on Wireless Communication, Network and Multimedia Engineering (WCNME 2019)

Design and Layout Optimization of the Interconnection Structure of Stretchable Circuits

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Abstract—Aiming at the crosstalk problem caused by unreasonable structure design and layout between interconnect wires of stretchable integrated circuits, a plan based on response surface method was proposed to optimize the structure and layout of stretchable circuits. Extensible universal interconnection structure of flexible circuit was taken as the research object and the parameters of conductor structure and layout were taken as design factors. The experimental design was carried out by using the center complex method and sample data was obtained by central composite design, and response values were obtained by ANSYS Electronic Desktop. Then second-order polynomial response surface model between crosstalk and influence factors was fitted. The optimization model was established with the minimum value of the sum of near crosstalk and far crosstalk as the optimization objective. A reference for the optimization and layout of the stretchable universal interconnection structure was provided.

Keywords—response surface method; stretchable circuit; general interconnection structure; crosstalk

I. INTRODUCTION

Flexible and stretchable circuits were widely used for their good bending and deforming abilities. Similar to traditional inorganic circuits, the effect of the structure parameters and layout density of interconnect wires on crosstalk could not be neglected as the transmission signal frequency increased. When crosstalk exceeded a certain range, the signal integrity will be seriously affected and the circuit system will not work properly.

It's one of the important requirements of circuit design to ensure signal integrity. There has been a wide range of research results in integrated circuit design and PCB design. For flexible and stretchable electrons, the signal integrity is also the main link of its reliability design. Therefore, many scholars have studied the signal integrity. Ye Zhihong [1] et al. constructed the crosstalk model of multi-conductor transmission lines with different heights by using time-domain transmission line equation, and obtained the crosstalk response of the end load of the transmission line. Ziming Dong[2] et al. conducted a simulation study on the electrical characteristics of horseshoe-shaped interconnection wires after deformation. An Gang[3] et al. proposed a new algorithm to study the electrical properties of serpentine interconnect structures under different strains. Huang Y[4] et al. studied the electrical properties of the island bridge structure of malleable energy storage device under certain strain and cycle conditions. Yan Wang [5] et al. studied the electrical properties of the improved inkjet printed circuit wires under different degree of folding state.

The above studies analyzed the signal integrity from different perspectives. Since the flexible extendable circuit is a newly developed technology in recent years, its signal integrity analysis and design are still in the initial stage. The influence of structure parameters, layout and working conditions on crosstalk is not considered comprehensively. To solve this problem, the research object was based on the coupling stretchable universal interconnection structure, using the response surface method function equation between the related factors and crosstalk, qualitative analysis of the impact of its to the crosstalk. According to design requirements to optimize response surface model and then get reasonable design and layout of conductor structure, which could ensure good electrical performance of the circuit

II. ESTABLISHMENT OF SIMULATION MODEL OF COUPLING GENERAL INTERCONNECTION STRUCTURE

A single period of extensible universal interconnection structure[6] was shown in Figure 1. The structure was mainly composed of horizontal segment *H*, radius *R*, angle *A* and oblique segment *T*. The particularity of the structure was the shape of the whole model mechanism changes with the geometric parameters, so it could be transformed into the other common extensible interconnection structure .

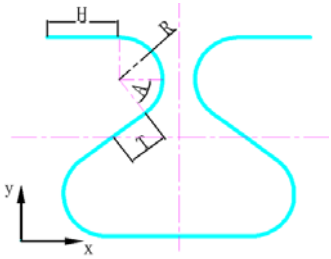

FIGURE I. SCHEMATIC OF SINGLE PERIOD OF STRETCHABLE UNIVERSAL INTERCONNECT STRUCTURE

In order to simulate crosstalk in flexible circuits, a three-wire coupled circuit model was designed based on the actual circuit model. The geometric parameters of the three transmission lines in the coupling circuit are identical, in which conductor 1 was the attack line and conductor 2 and 3 are the victimization lines. The conductor model was set to three-layer sandwich structure. In order to ensure two conductors were not intersected, it was necessary to ensure the distance d was greater than the distance h between the two conductors, as shown in Figure 2. When *d* was 1, The distance between two lines was h, and *d* was 2, The distance between two lines was 2 h, and so on. According to the geometric relationship, the value

of h can be calculated by the formulation $h = 2R + 2R * sinA + 2T * cosA$.

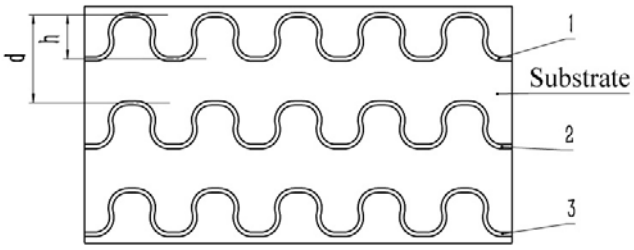

FIGURE II. SCHEMATIC OF STRETCHABLE FOR GENERAL INTERCONNECTION STRUCTURE OF CIRCUIT MODEL

III. ESTABLISHMENT OF ELECTRICAL OPTIMIZATION MODEL BASED ON RESPONSE SURFACE METHOD

A. Test Design

The significant influencing factors selected by orthogonal test, such as horizontal segment *H*, angle *A*, radius *R*, oblique segment *T*, frequency *f* and distance *d* were taken as design variables, the design parameters with smaller influence factors in the wire was selected according to specific requirements. For qualitative analysis of design variables, all conductors were set as 0.02 mm in width, 0.005 mm in thickness and 2 mm in length, Specific experimental factors and variation intervals were shown in Table 1.

Central Composite Test Design [7,8] was one of the most commonly method for fitting response surface, which could effectively evaluate the non-linear effects of factors and the interaction between factors. The experimental design is carried out by using the face-centered method [9], which is not easily affected by the source of experimental errors and leads to the failure of the analysis results. Using ANSYS Electronic Desktop to get the required crosstalk data. The simulation results show that under the design conditions in this paper, the results of the line 3 meet the requirements of the actual working conditions, so it was only need to analyze the crosstalk of the victimization line 2. The results of the line 2 were shown in Table 2, in which S13 was near end crosstalk and S14 was far end crosstalk.

TABLE I. ANALOG CIRCUIT TEST FACTOR

Factor	Lower bound	Upper bound
H(mm)	0	0.04
A(°)	0	30
R(mm)	0.06	1
T(mm)	0	0.02
f(GHz)	1	5
d	1	3

TABLE II. CENTER COMPOSITE DESIGN

No.	Factor						Response value	
	H/mm	*A/°*	*R/mm*	*T/mm*	*f/GHz*	*d*	*S13/dB*	*S14/dB*
1	0.02	15	0.08	0.01	3	2	-21.2484	-22.2476
2	0	15	0.08	0.01	3	2	-21.573	-22.6061
3	0.04	15	0.08	0.01	3	2	-21.3232	-22.3415
4	0.02	0	0.08	0.01	3	2	-20.1817	-21.1686
5	0.02	30	0.08	0.01	3	2	-22.6808	-23.7104
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
43	0.04	0	0.1	0.02	5	1	-16.5757	-17.3156
44	0	30	0.1	0.02	5	1	-19.832	-19.6048
45	0.04	30	0.1	0.02	5	3	-26.7518	-26.5899

B. Establishment of Response Surface Model

The response surface model was established by the full second-order polynomial method, and its mathematical expression was shown in equation (1):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i}^{k} \sum_{j}^{k} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 \tag{1}$$

Where β is regression coefficient, x is impact factor, y is response value.

The regression coefficient was determined by the least square method, and the crosstalk response surface formula obtained by the final fitting.

Near end crosstalk function expression was equation (2):

$$\begin{aligned} M(H,A,R,T,f,d) = & -14.5 - 29.3H + 0.0798A - 236R + 22.2T + 6.780f - 5.54d + 52H^2 + 0.000001A^2 + 1341R^2 + \\ & 175T^2 - 0.7594f^2 + 0.808d^2 + 0.342H*A + 30H*R + 152H*T + 5.57H*f + 4.63H*d - 0.554A*R + 0.386A*T - \\ & 0.01502A*f - 0.03453A*d + 96R*T - 1.31R*f - 3.30R*d - 12.59T*f - 26.55T*d + 0.0343f*d \end{aligned} \tag{2}$$

Far end crosstalk function expression was equation (3):

$$N(H,A,R,T,f,d) = -25.12 + 19.1H + 0.0168A - 40.6R - 30.8T + 6.622f - 3.560d - 254H^2 - 0.000299A^2 + 183R^2 - 681T^2 - 0.0.6863f^2 + 0.672d^2 + 0.329H*A - 148H*R + 252H*T + 1.86H*f + 0.07H*d - 0.220A*R + 0.101A*T - 0.00714A*f - 0.02516A*d + 465R*T - 1.48R*f - 16.46R*d - 5.58T*f - 17.58T*d - 0.0130f*d \quad (3)$$

The fitting accuracy of the regression model was tested, and the results are shown in table 3.

R^2 and R_{adj}^2 are used to measure the degree of fitting of the model, the value range is 0-1, and the closer the value is to 1, the better the fitting degree of the model is. R_{pred}^2 is indicated the predictive ability of the model, and the same value range is 0-1, and the closer the value is to 1, the better the predictive ability is. From Table 3, It can be seen from table 3 that R^2 and R_{adj}^2 are approximately equal to 1, so the model has a good degree of fitting. The prediction determination coefficient is also approximately equal to 1, so the model has good prediction ability and can be used for further optimization of type selection and layout.

TABLE III. ERROR CHECKING

	S13	*S14*
R^2	0.9978	0.9991
R_{adj}^2	0.9943	0.9976
R_{pred}^2	0.9798	0.9915

C. Establishment of Optimization Model

An optimization model of extensible universal interconnection structure was established based on the response surface model constructed. *H*, *A*, *R*, *T*, *f* and *d* were variable design parameters in the model, and the range of variation was the upper and lower limits for each variable. Under the condition that both near end crosstalk and far end crosstalk are less than -20dB, the general optimization model for minimizing crosstalk was as follows:

$$\begin{aligned} &\min(M(H,A,R,T,f,d) + N(H,A,R,T,f,d)) \\ &s.t. \quad 0 \le H \le 0.04mm \\ &\qquad 0 \le A \le 30° \\ &\qquad 0.06 \le R \le 0.1mm \\ &\qquad 0 \le T \le 0.02mm \\ &\qquad 1 \le f \le 5GHz \\ &\qquad 1 \le d \le 3 \\ &\qquad M(H,A,R,T,f,d) \le -20dB \\ &\qquad N(H,A,R,T,f,d) \le -20dB \end{aligned} \quad (4)$$

Referring to the general optimization model, the constraints could be changed to meet the design requirements, and the optimal values of each variable could be obtained by combining the optimization method. The optimal traverse structure and layout under the design requirements could be obtained.

IV. CASE OPTIMIZATION

The interconnection structure and layout optimization were solved to verify the effectiveness of the optimization model.

A. Case Introduced

At present, the mainstream structure of extensible electronic products was Island Bridge structure, as shown in Figure 3. In the Island Bridge structure, the span between islands was 2 mm. The production requires that the extensible universal interconnection structure could satisfy the following conditions: under the condition of 1 GHz frequency and 2 mm size of Island Bridge, the total height of the line was required to be less than the height of the island, and ensure the crosstalk of the extensible universal interconnection structure line was minimum. According to the above requirements and the initial setting parameter range of the extensible universal interconnection structure, the interconnection structure was optimized.

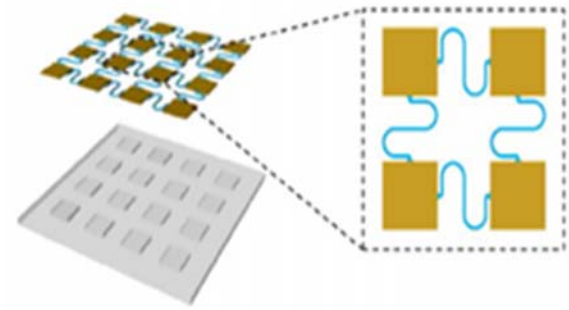

FIGURE III. ISLAND BRIDGE[10]

B. Establishment of Case Optimization Model

Establish the optimization model with the requirements of the case based on the above optimization model constructed. In order to satisfy the requirements that the circuit height is less than the island height, the constraints $(2d+1)*h+0.08 \le 2mm$ and the fixed constraints f=1GHz should be added. Finally, the optimization model was constructed.

$$
\begin{aligned}
&\min(M(H,A,R,T,f,d)+N(H,A,R,T,f,d)) \\
&s.t. \quad 0 \le H \le 0.04mm \\
&\qquad 0 \le A \le 30° \\
&\qquad 0.06 \le R \le 0.1mm \\
&\qquad 0 \le T \le 0.02mm \\
&\qquad f = 1GHz \\
&\qquad 1 \le d \le 3 \\
&\qquad M(H,A,R,T,f,d) \le -20dB \\
&\qquad N(H,A,R,T,f,d) \le -20dB \\
&\qquad (2d+1)*h+0.08 \le 2mm
\end{aligned} \tag{5}
$$

C. Results of Analysis and Verification Optimization

According to the established optimization model equation (5), relevant settings are set in the ANSYS software optimization module, and the ANSYS sequential quadratic programming method is used for optimization solution. In order to verify the effectiveness of the optimization results, which was compared with the conductor model data of the three random groups that meet the requirements of interconnection structure design. The results were shown in table 4. Compared with the other three groups of extensible general interconnection structure, the electrical properties of the circuit performance of the optimized interconnection structure were improved and the crosstalk between conductors was significantly reduced. The optimal structural design and layout for: H = 0, A = 30 °, R = 0.0816 mm, T = 0.02 mm, d = 2.935, the corresponding near end crosstalk is 32.048 dB, far end crosstalk is 34.09 dB, more in line with the circuit design requirements.

According to the optimization results, the analog circuit model was established and imported into ANSYS Electronic Desktop for crosstalk analysis. The calculation results were shown in Table 5. Compared with the simulation results and the results of sequential quadratic optimization, the errors of near-end crosstalk and far-end crosstalk were less than 3.5%, and the simulation errors were small, which proved that the optimization results had high reliability.

TABLE IV. RESULTS OF THE OPTIMIZATION

	H/mm	*A/°*	*R/mm*	*T/mm*	*f/GHz*	*d*	*S13/dB*	*S14/dB*	*S*
0	0	0	0.06	0	1	1	-23.022	-24.922	-47.944
1	0	30	0.0816	0.02	1	2.935	-32.048	-34.09	-66.138
2	0	16.588	0.1	0.0043	1	1.5286	-27.518	-28.254	-55.772
3	0.0002	9.371	0.1	0.0029	1	1.0863	-25.303	-26.455	-51.758

TABLE V. RESULTS OF COMPARISON OF SIMULATION AND OPTIMIZATION

	S13/dB	*S14/dB*
Results of simulation	-32.048	-34.09
Results of optimization	-31.93628	-33.41863
Error (%)	3.48	1.97

V. SUMMARY

(1) The sample points were obtained by using the central composite test design, and the crosstalk values between the interconnection structures in the flexible and stretchable circuit were obtained by using ANSYS Electronic Desktop. The response surface model between crosstalk, structural parameters and wiring mode was constructed by using the quadratic polynomial. The optimization efficiency was improved by this method.

(2) According to the response surface model, a general optimization model of the simulation circuit was established. In combination with practical cases, the optimization model was optimized by using the quadratic sequence programming method, and the structure and arrangement mode of the interconnected wires with the minimum crosstalk under specific conditions are obtained. A theoretical reference for the design and optimization of the flexible and stretchable circuit were provided.

ACKNOWLEDGEMENT

This work is supported by National Science Foundation of China (Grant No.61474032).

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