An optimization method for conformal shielding

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Abstract Conformal shielding, as an efficient method for solving the electromagnetic interference (EMI) problem, is becoming increasingly important. In this Letter, the Taguchi method in quality engineering was introduced into the design optimization of conformal shielding. As a pilot test, the authors studied the order of the effects of shielding layer material, shielding layer thickness, and distance between ground vias (D-via) on shielding effectiveness (SE). The comparison between simulated results and predicted results proves that the optimization method is accurate and effective. The thin-film conductivity of copper was measured, and the model was revised using the measurement results. For validation, built a near-field scanning platform, and measured shielding effectiveness and simulated shielding effectiveness show a good agreement from 0.1 to 7.5 GHz.

Keywords: Taguchi method, design optimization, shielding effectiveness, thin-film conductivity, near-field scanning

Classification: Electromagnetic theory

1. Introduction

With the continuous improvement of system integration, EMI problems are aggravated for shortened distance between noise sources and sensitive circuits [1]. Conformal shielding, as an efficient method for solving EMI problems, is becoming increasingly important. The primary goal in all conformal shielding design is to improve the SE. While an amount of the existing literature focused on the influence of shielding layer material and shielding layer thickness on SE [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. There were also a number of studies on SE measurement methods in [13, 14, 15, 16, 17] and probe calibration in [18, 19, 20, 21]. Moreover, some fast approaches were presented for the evaluation of near field SE in [22, 23, 24, 25, 26]. However, there is little discussion about design optimization.

The conventional method of optimization is to make the product performance satisfy specifications by using statistical approaches. However, this method is complicated and not cost-effective, due to its requirement of extensive and time-consuming calculation work. Richard Xian-Ke Gao presented a robust design approach based on the Taguchi method that not only optimizes the absorption efficiency of an electromagnetic wave absorber over a wide bandwidth, but also reduces the sensitivity of the optimized performance to a number of uncontrolled variables in [27, 28]. In [29], the Taguchi method was used to optimize the heat sink geometry parameters to minimize electromagnetic radiation from the flat plate heat sink. In [30], the authors presented a design of a multistage pulsed power induction coilgun system using the Taguchi method to maximize its efficiency and reduce the time and cost of the design process. The Taguchi method was also applied in optimal design of jiles-atherton, hysteresis model, surface-mounted permanent magnet motor, cpw slot antennas, and band/polarization patch antenna in [31, 32, 33, 34]. The Taguchi method has been widely used in both mechanical engineering and electrical engineering [27].

In this Letter, the Taguchi method is applied to the design optimization of conformal shielding. The purpose is to optimize the SE over a wider bandwidth, and the experiments are configured according to the orthogonal array (OA) scheme. The optimizable performance index is defined by the ratio of signal-to-noise (S/N) to represent the SE of conformal shielding. The influence of each variable on the performance is analyzed, and the optimum settings of the design parameters are obtained. Finally, the conformal shielding sample is prepared by sputtering technique, and a near-field scanning platform is built. The comparison between measured SEs and simulated SEs from 0.1 to 7.5 GHz shows a good consistency.

2. Taguchi method

The Taguchi method is based on probability and mathematical statistics. It is a mathematical statistics method for arranging experiments and analyzing data. According to Taguchi’s philosophy, the design factors in a system can be divided into two groups: noise factors and control factors. While the control factors, which have a significant impact on system performance, can be controlled by the designer, the noise factors are usually random but have a lesser impact [28]. In this letter, the control factors of shielding conformal are shielding layer material, shielding layer thickness, and D-via. An OA is applied to construct the experiments after design factors have been identified and classified [27]. In this study, an OA L9 can be used for three factors with three levels, which requires only nine experiment runs while the conventional statistical optimization method needs \(3^3 = 27\) runs to yield the same result. The level values (based on existing literature) and the OA L9 are shown in Table I.

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In the Taguchi method, the S/N is a measure of robustness and used to identify control factors that reduce variability in a product or process by minimizing the effects of noise factors. Higher values of the S/N identify control factor settings that minimize the effects of the noise factors. Based on different target characteristics, S/N can be divided into three typical calculation models: the first model is the “Smaller is better”, the second model is the “Larger is better”, and the third model is the “Nominal is best”. The goal of design optimization is to maximize the SE of conformal shielding, therefore the second model is applied in this study. The mean, which is the average response for each combination of control factor levels, is another important parameter in the Taguchi method. The S/N and the mean are calculated with the following expression

\[
S/N = -10 \times \log\left(\frac{1}{n} + \frac{1}{y_1} + \ldots + \frac{1}{y_n}\right)
\]

\[
\text{Mean} = \frac{y_1 + y_2 + \cdots + y_n}{n}
\]

Where \(y\) represents SE observed in every run of the experiment, and \(n\) is the number of runs in the experiment. Analysis of mean (ANOM) is a useful instrument for obtaining the significance of control factors for the S/N and mean.

In this letter, ANOM is completed with Minitab software.

4. Conformal shielding design optimization

Each row in Table I represents different control factors’ levels combination. Nine groups of models were established in ANSYS HFSS software corresponding to different control factors’ levels combination. Based on product characteristics of Henkel Adhesives, the conductivity of Ag was set to 2.6 \times 10^3 S/m in models. It should be noted that the bulk conductivity of copper and nickel were used in simulation models, which are 5.8 \times 10^2 S/m and 1.45 \times 10^2 S/m, respectively. On the other hand, unlike the permeability of bulk nickel case, the permeability of sputtered nickel decreases exponentially around 1 MHz. After 1 MHz, the relative permeability approaches to 1 [3, 14]. The observation surface was located 2 mm above the models, and the size was set to 20 \times 20 mm^2 to entirely capture the electromagnetic field radiated from the microstrip line. According to the spatial resolution of 1 mm in both x- and y-directions, the observation surface was divided into 441 observation points. The SE is defined as

\[
SE_R = 20 \log_{10}\left|\frac{H_{\text{unshield}}(R)}{H_{\text{shield}}(R)}\right|
\]

\[
SE = \max(SE_R)
\]

Where \(H_{\text{unshield}}(R)\) and \(H_{\text{shield}}(R)\) are the tangential magnetic fields without and with conformal shielding, respectively, and \(R\) is the observation point on the observation surface. \(SE_R\) represents the magnetic field SE of a single point. Equations (3) and (4) were used to calculate the SE of conformal shielding at 0.1, 0.75, 2.4, 4.8, 7.5 GHz frequencies, and the results are summarized in Table II.

### Table II The results of OA L9

| Number | 0.1 GHz | 0.75 GHz | 2.4 GHz | 4.8 GHz | 7.5 GHz |
|--------|---------|---------|---------|---------|---------|
| 1      | 29.92   | 47.33   | 57.74   | 64.07   | 68.92   |
| 2      | 39.52   | 56.47   | 65.00   | 70.62   | 75.14   |
| 3      | 45.30   | 60.35   | 69.97   | 76.98   | 82.63   |
| 4      | 3.44    | 1.25    | 5.79    | 11.64   | 16.74   |
| 5      | 0.56    | 5.62    | 14.89   | 21.39   | 26.13   |
| 6      | 0.73    | 10.17   | 20.07   | 26.70   | 32.22   |
| 7      | 18.51   | 35.63   | 45.55   | 52.22   | 57.42   |
| 8      | 27.39   | 44.76   | 54.75   | 60.99   | 65.63   |
| 9      | 33.47   | 50.33   | 59.61   | 65.59   | 70.27   |

ANOM is carried out to determine the best combination of control factors that achieves optimal performance [28]. ANOM processes the simulation results from two aspects, and obtain the response table for means and the response table for S/N. Taking the 0.1 GHz as an example, ANOM
Table III  Response table for means at 0.1GHz

| Level | Material | Thickness | D-via |
|-------|----------|-----------|-------|
| 1     | 38.2467  | 16.2567   | 19.3467|
| 2     | 0.5433   | 22.4900   | 24.4433|
| 3     | 26.4567  | 26.5000   | 21.4567|
| Delta | 37.7033  | 10.2433   | 5.0967 |
| Rank  | 1        | 2         | 3      |

Table IV  Response table for S/N at 0.1GHz

| Level | Material | Thickness | D-via |
|-------|----------|-----------|-------|
| 1     | 31.526   | 15.166    | 18.513|
| 2     | -5.713   | 18.551    | 17.686|
| 3     | 28.198   | 20.294    | 17.811|
| Delta | 37.239   | 5.128     | 0.826 |
| Rank  | 1        | 2         | 3      |

It can be seen from Table IV that when the material changes, the S/N response changes most drastically. This result indicates that material has the most significant impact on SE, followed by thickness, and D-via has the weakest effect. Furthermore, among the three levels of materials, level 1 (Copper) has a better performance on S/N than other two levels. Different from material and thickness, the three levels of D-via have similar results. It is interesting to note that in all five frequencies of this study, we can get the same conclusion as when the frequency is 0.1 GHz.

In conclusion, according to ANOM, the final level combination for the control factors is, material, copper; thickness, 6 μm; D-via, 400 μm. In comparison to the level combination for the control factors in OA L9 (Table I), the final level combination for the control factors is different. Therefore, the Taguchi prediction module in Minitab was used to quickly predict SE response in all frequencies. Fig. 2 shows a comparison between the simulated SEs and the predicated SEs under the final level combination for the control factors. The predicted results are consistent with the simulated results. The deviation is less than 2 dB at all frequencies. This result proves the effectiveness of the Taguchi method in the design optimization of conformal shielding.

5. Shielding measurement setup

A near-field measurement setup was established to evaluate SE of conformal shielding as demonstrated in Fig. 3. It is based on the surface scanning method according to IEC 61967-3. The instruments included a signal generator, a spectrum analyzer, an automatic scanner, a H probe and a ground plane. The signal generator was connected to the microstrip line inside the test vehicle through the SMA connector. The automatic scanner was used to control the direction and step of the H probe. Aiming to obtain the field information at the observation surface, the H probe was connected to the spectrum analyzer with a low-loss cable. Since the electromagnetic energy after shielding was weak, a H probe with a larger head diameter and higher sensitivity was required, which inevitably sacrificed resolution. To reduce the influence of the possible magnetic field leakage, the SMA connector was placed on the back of the PCB and a circle of copper foil was added around the ground plane. Considering that the PCB also has magnetic field leakage, and covered it with a circle of copper foil. The measurement settings were consistent with the simulation. The scanning area was located 2 mm directly above the DUT, and the size was $20 \times 20 \text{ mm}^2$. By automatically controlling the scanner, the radiation was scanned with a spatial resolution of 1-mm step along with both x- and y-directions. In the scanning process, when video bandwidth and resolution bandwidth for the mean and S/N corresponding to each level of the three control factors was analyzed (Table III and Table IV). The units in Table II, Table III, and Table IV are dB. The Delta in Table III and Table IV is the difference between the maximum response and the minimum response. A larger Delta means that the control factor has a more significant influence on the mean and S/N.

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Fig. 2  Simulated and predicted SEs of conformal shielding

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Table V  Equipment parameters in measurement system

| Equipment       | Parameter Description                      |
|-----------------|-------------------------------------------|
| Signal generator| Frequency range: 100 KHz - 43.5 GHz       |
| Spectrum analyzer| Frequency range: 10 Hz - 40 GHz          |
| Automatic scanner| Scanning area: $20 \times 20 \text{ mm}^2$|
| H probe         | Frequency range: DC - 20 GHz             |

![Fig. 3](image-url)
of the spectrum analyzer were set to 1 MHz and 20 Hz respectively, the displayed average noise level was -140 dBm, and scanning time of a single frequency point was 6.5 hours. The whole scanning process consumed a lot of time. On the basis of meeting the minimum signal level, increased resolution bandwidth to 500 Hz and controlled displayed average noise level at -130 dBm. Meanwhile, scanning time of a single frequency point decreased from 6.5 hours to 1.2 hours. The equipment parameters set in the measurement system are shown in Table V.

6. Comparison SE results

As a commonly used shielding material, copper plays a critical role in electromagnetic shielding. It is worth noting that there is a significant difference between its bulk conductivity and thin-film conductivity. In [22], the bulk conductivity of copper was applied to the conformal shielding formed by sputtering technology, which caused differences between the simulation results and the measurement results. The thin-film conductivity of copper at 0.1-10 MHz was measured in [3]; nevertheless, the measurement results cannot be applied over a wider frequency band.

In the material library of ANSYS HFSS, the bulk conductivity of copper is $5.8 \times 10^7$ S/m. However, the conductivity of thin-film formed during the sputtering process is different from that of the bulk. Therefore, it is necessary to measure the thin-film conductivity of copper. Sputtering technology was used to prepare “Copper-6 μm-400 μm“ test samples and the thin-film conductivity test samples. Due to process defects, the thickness of the shielding layer of the actual test sample was 3 μm. The thin-film conductivity of copper, which was tested by two different the four-probe measurements, was $2.104 \times 10^7$ S/m and $2.134 \times 10^7$ S/m respectively. It can be considered that $2.1 \times 10^7$ S/m was a reasonable value for the thin-film conductivity of copper.

The model was revised according to the thin-film conductivity of copper and the shielding layer’s thickness of the actual test sample. Fig. 4 shows the comparison between simulated SEs and measured SEs at 0.1, 0.75, 2.4, 4.8 and 7.5 GHz. The maximum deviation appears at 4.8 GHz, and its value is about 3 dB. Fig. 5 and Fig. 6 show the field patterns of the tangential magnetic field at 4.8 GHz with and without conformal shielding respectively. The black and red lines are the positions of the DUT and the SMA connector, respectively, and the upper SMA is connected to the excitation. In Fig. 5, the tangential magnetic field of the radiation source is large enough that the overall field pattern is not easily affected by environmental radiation. In Fig. 6, the tangential magnetic field of the radiation source attenuates sharply that the overall field pattern is more sensitive to environmental radiation, especially the radiation from the upper SMA connection. Furthermore, in the yellow line area, the electromagnetic radiation from the PCB is coupled to the scanning plane through the copper foil. Ignoring the interference from environment, there is a good agreement between simulated SEs and measured SEs, which shows the validity of the thin-film conductivity of copper from 0.1 to 7.5 GHz.

Comparing Fig. 2 and Fig. 4, we can see that they have the same trend, but there are differences in value. This difference can be divided into two groups: caused by thickness and caused by conductivity. On the one hand, the shielding layer thickness of the simulation model in Fig. 2 was set to 6 μm, but the shielding layer thickness of the revised model was 3 μm due to process defects of sputtering technology in Fig. 4. On the other hand, the bulk conductivity of copper was applied to simulation model in Fig. 2. However, the model in Fig. 4 was modified with thin-film conductivity of copper measured by the four-probe measurement. In section 4, we concluded that D-via has indistinctive effect impact.
on SE. Therefore, we made an approximation, ignoring the difference caused by D-via, and compared the simulation result of model 2 (“Copper-3µm-800µm”, conductivity of copper is $5.8 \times 10^7$ S/m) in Table II with simulation result of revised model (“Copper-3µm-400µm”, conductivity of copper is $2.1 \times 10^7$ S/m). The difference between them is the effect of conductivity on SE. The difference caused by thickness was obtained by doing a subtraction between the overall difference and the difference caused by conductivity. Fig. 7 shows the relationship of the three kinds of differences with frequency. From Fig. 7, we can see that the difference caused by conductivity is greater than the difference caused by the thickness at all frequencies, which is consistent with the analysis in section 4.

7. Conclusion

The Taguchi method was introduced for the first time in the conformal shielding design. By using the Taguchi method, not only is the SE of conformal shielding optimized over a wider frequency band, but also the simulation time is significantly reduced even though some design parameters could be extended and changed due to processing and manufacturing. However, the proposed design optimization is always applicable. The thin-film conductivity of copper was measured by the four-probe method. The consistency between the near-field scanning results and the simulation results further proves the validity of the thin-film conductivity of copper. Future work will focus on how to reduce the sensitivity of the optimized performance to a number of hard-to-control variables.

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