INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2025, VOL. 71, NO. 1, PP. 113-121
Manuscript received July 04, 2024; revised March 2025. doi: 10.24425/ijet.2025.153552

Manufacturing and design practices: a review of crosstalk reduction in electronic circuit

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Abstract—**Electronic circuit boards are components widely used in applications requiring modern high-speed signal transmission. This study aims to comprehensively examine various methods used in the design and manufacturing stages of electronic circuit boards and to focus on strategies for reducing crosstalk. In addition, the effects of these methods are thoroughly analyzed by comparing simulation results and laboratory tests found in the literature. Effectively managing crosstalk can aid in preserving signal integrity in circuits characterized by high speed and density.**

Keywords—**crosstalk noise; signal integrity; circuit design; printed circuit; manufacturing techniques**

I. INTRODUCTION

CROSSTALK occurring on electronic circuit boards is very important for signal integrity. Nowadays, electronic systems and devices are changing rapidly, and this change points to a period in which faster data transmission, increased processing capacity and advanced functions are demanded. These demands go beyond electronic circuit design and bring about various challenges in signal transmission and processing. One of these difficulties is the crosstalk problem. In electronic circuits, crosstalk refers to the undesirable electromagnetic interaction between signals that occurs as a result of increasing speed and complexity.

This can seriously affect signal integrity and the overall performance of the circuit. The significance of crosstalk becomes even more pronounced with the increasingly dense integration processes and the need for high-speed operations in modern electronic circuits [1]. Today, it is observed that processor speeds and densities are continuously increasing. The growing density leads to a reduction in the distance between transmission lines on the electronic circuit board [2]. The adjacency of data transfers occurring between blocks on the circuit contributes to crosstalk between these transmission lines [3].

Additionally, fields such as wireless communication and high-speed data transfer are rapidly expanding. This development has added new dimensions to electronic circuit design and further emphasized the effects of crosstalk. The reduction of crosstalk between transmission lines becomes even more crucial for high-speed applications [4].

The effects of crosstalk extend beyond just signal integrity, encompassing a range of key factors such as noise levels and overall system performance. Signal distortions can compromise reliability and lead to interruptions in the operation of a system. To address this electromagnetic interaction issue, the use of guard traces, curved traces, or shielding fences is recommended [5]. In addition, screening techniques have been examined to suppress unwanted noise, offering solutions to mitigate this current issue [6]. While shielding is generally a straightforward solution, it may not provide protection for certain transmission lines [7].

The risk of unwanted electromagnetic interactions in electronic circuits adversely affecting signal integrity further underscores the importance of crosstalk. Especially in modern electronic circuits operating at high frequencies and requiring fast signal transition, the effects of crosstalk can lead to signal distortion, data loss, as well as impacting the delay of transmitted signals and the stability of the system [8]. Additionally, guard traces placed between transmission lines can be employed in various configurations [9].

Physical components such as parasitic-suppressing capacitors and inductors used in signal path lengths play a critical role in reducing the effects of crosstalk. The study conducted by Sehat and Masoumi [10] focuses on the analysis of crosstalk noise in electronic circuits with transmission lines of varying lengths, representing a significant contribution to research in the field of printed circuit board (PCB) design.

Design and manufacturing methods are among the fundamental tools engineers use to reduce the effects of crosstalk. In electronic circuit design, strategies such as isolation techniques, line arrangements, low-pass filters, and electromagnetic compatibility (EMC) measures can be employed to minimize the effects of crosstalk. Minimizing the lengths of transmission lines prevents signal delays and enables high performance [11]. Achieving optimal conditions for signal transmissions can prevent issues and crosstalk [12].

The various methods employed to prevent crosstalk and manage electromagnetic interactions constitute a significant aspect of electronic design and manufacturing. These methods undergo theoretical analyses as well as practical applications, being tested and refined. In this article, drawing upon studies in the literature, different design and manufacturing methods used to prevent the effects of crosstalk and manage electromagnetic interactions are discussed. The impact of these methods on the performance of electronic circuit boards is examined, exploring strategies to minimize the adverse effects of crosstalk and enhance the signal integrity and overall performance of electronic systems. Therefore, this study aims to delve into the

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depths of electronic design, seeking to uncover the roots and essence of the crosstalk problem.

A. 3W, SGT and VSGT methods

The effects of crosstalk are being investigated with the aim of suppressing or minimizing them through various design strategies and techniques. Ground-plane shielding is commonly employed to enhance signal integrity performance and suppress crosstalk [13]. Choi et al. [14] in their research demonstrate that the addition of transitions, referred to as stubs, to the shielding traces between transmission lines can be beneficial in reducing crosstalk.

The study conducted by Huang et al. [15] introduces a creative solution to the issue of crosstalk. This research examines the effects of via connections placed on serpentine (curved) shielding traces between transmission lines on crosstalk. The conducted experimental studies support the effectiveness of this novel approach, providing an alternative solution to the crosstalk problem in electronic circuit design. In this study, the effectiveness of the widely accepted 3W rule and the proposed new design approach, the serpentine guard trace (SGT), and the via of serpentine guard trace (VSGT) model were examined. Here, it can be observed that transmission lines are routed parallel on a circuit board. However, in real-world applications, non-parallel transmission lines can also be routed together for a certain distance. In the case of non-parallel transmission lines, the creation of transition structures allows for the reduction of crosstalk.

The 3W rule is based on the "W" parameter, which represents the thickness of the transmission line, and it specifies that the minimum distance between two different transmission lines should be three times the thickness of the transmission line. To minimize the issue of crosstalk, extra spaces should be added between traces. This 3W rule is a widely used method to prevent or minimize crosstalk problems. However, the study by Huang et al. [15] aims to go beyond this rule and proposes alternative design approaches.

The effects of crosstalk can be significantly reduced by adjusting the distance between via connections in the SGT design. This design can enhance signal integrity by optimizing the distance between the transmission line and the reference plane. The VSGT model, on the other hand, can be considered as a further advancement of this design. Through the use of transitional curved guard traces, additional connections are established between more transmission lines and the reference plane, effectively reducing crosstalk effects. It is well-known that utilizing guard traces between transmission lines is an effective method for suppressing crosstalk [16].

B. Thickened Solder Mask Coated Microstrip Lines

The article authored by Yu et al. [17] explores a different approach to solving the crosstalk problem. The focus of the paper is on investigating microstrip lines with thickened solder mask coating to reduce crosstalk in high-speed PCB designs. In high-speed double data rate 5 (DDR5) PCB designs, minimizing the effects of crosstalk is crucial for preserving signal integrity and increasing data transmission speeds.

The approach presented in the article highlights how thickened solder mask-coated microstrip lines can be effectively used in the design and manufacturing processes. Experimental studies and analyses conducted in the research demonstrate the potential of this approach to provide a solution for reducing crosstalk. Yu et al. [17] research mainly examines the effects of paint on copper transmission lines, called 'soldermask' in the industry. Copper transmission lines are placed on top of a dielectric material. Considering the side section view, the height of the regions where transmission lines are located is higher than the regions where only dielectric material is located. The main reason for this height difference is that the copper has a certain height along the transmission line. Copper height can be changed according to preference. Considering this feature, this study examines the effects of covering the area between transmission lines and having a lower height along the transmission line plane with a solder mask at the same distance as the transmission line. Both the scenario in which the entire surface is covered with solder mask at the same height and the scenario in which the transmission lines are exposed to more solder mask until the spacing is equalized are discussed separately with a detailed analysis of crosstalk levels.

C. Coverlay coating method

In electronic circuit design, coverlay is typically a thin film or coating, often made of a polymer material, that covers the surface of a circuit board. Coverlay is used to protect, insulate, and enhance the mechanical durability of the components and traces on the circuit board. Additionally, it serves the function of shielding circuit elements against environmental and external factors. Such coatings are commonly employed in circuit designs that require high speed and intensive integration. Coverlay applications can improve the reliability of circuit boards and offer greater flexibility in the design processes [18].

The study conducted by Cai et al. [18] thoroughly examines the effects of coverlay coatings applied to microstrip lines for the reduction of crosstalk. The article offers a potential solution to mitigate the crosstalk problem by analyzing the design parameters of coverlay coatings and their impacts on microstrip lines. However, extensively examines the effects of various design parameters, such as coating thickness and position, on crosstalk.

Cai et al. [18] and Yu et al. [17], similar to their counterparts in other studies, have paid particular attention to the height differences between transmission lines. Therefore, they conducted simulations of crosstalk by applying the coverlay process at the same level on both the transmission line and the PCB surface. Additionally, they extensively examined crosstalk by creating a structure where the space between and above the transmission lines underwent the coverlay process.

D. Via fences method and victim line optimization

Via fences are used to reduce crosstalk in high-speed PCB circuits. These structures, defined as metallic formations placed between transmission lines, assist in preventing electromagnetic interactions. The study conducted by Suntives et al. [19] explores a new approach to addressing the crosstalk problem in PCB circuit designs. The article focuses on a specific design technique referred to as "via fences," and different configurations of these structures' impact on crosstalk are evaluated through simulations and experimental results. Parameters such as the spacing, dimensions, and locations of the via fences are discussed in terms of optimizing crosstalk reduction. Additionally, the feasibility of implementing this method should be assessed, taking practical factors into account, including the cost and design complexity of via fences.

Almalkawi et al. [20] designed a sacrifice line containing impedance discontinuities and studied its effect on crosstalk immunity.This study delves into the phenomenon of crosstalk occurring in designs involving gaps, guard traces, and transitional guard traces between transmission lines, a crucial aspect of electronic circuit design. In this context, an irregular transmission line incorporating continuous impedance discontinuity is referred to as the "victim line," while a linear transmission line is defined as the "aggressor line" [20].

E. Calculation of crosstalk

In the context of transmission lines, to identify aggressor and victim lines, it is necessary to first define the line to which the signal is applied. The line to which the signal is applied either functions as an aggressor line, emitting noise and interference to other lines, or it is a line that maintains its current state, referred to as a victim line, which can be affected by noise from surrounding lines.

Cross-talk noise is generally expressed in two types: near-end crosstalk (NEXT) and far-end crosstalk (FEXT) [21]. Near-end crosstalk is represented by NEXT, while FEXT represents far-end crosstalk. Near and far-end crosstalk are expressed as shown in (1) and (2). Here, Vin represents the input voltage, TD is the delay of the line, tr is the rising time, Ls is the self-inductance, Lm is the mutual inductance, CT is the total capacitance, and Cm is the mutual capacitance [22].

$$V_{next} = \frac{V_{in}}{4}\left(\frac{L_m}{L_s} + \frac{C_m}{C_T}\right) \tag{1}$$

$$V_{fext} = \frac{-V_{in} \times TD}{2t_r}\left(\frac{L_m}{L_s} - \frac{C_m}{C_T}\right) \tag{2}$$

F. Effect of surface coating on dielectric constant and role of insulation materials

In their study, Cai et al. [23] aimed to go beyond the crosstalk effects in DDR5 memory circuits. The approach discussed in the article focuses on protecting transmission lines and reducing crosstalk using a graphene-paraffin coating material. Specifically, attention has been directed towards structures called tabs associated with the transmission lines. The graphene-paraffin coating material used in these structures has the potential to limit crosstalk effects and reduce far-end crosstalk.

The article carefully examines the impact of transmission lines coated with graphene-paraffin material and the tabs structure on crosstalk. Simulation results indicate that this new approach can significantly reduce crosstalk in DDR5 memory circuits.

Zhang et al. [24] in their study, two main strategies have been combined to enhance the resilience of electronic circuit boards against crosstalk effects. Firstly, the surface of electronic circuit boards is coated with graphene-paraffin material. Graphene-paraffin material possesses advantages such as high conductivity and low dielectric loss, aiming to make the surface of electronic circuit boards more resistant to crosstalk effects. The second strategy involves arranging the transmission lines with protruding structures during the design phase. The protrusions added to the transmission lines target to suppress crosstalk by reducing electromagnetic interaction between adjacent lines.

Zhang et al.'s [25] article focuses on a new design strategy to mitigate far-end crosstalk (FEXT), a significant cause of crosstalk, by integrating a defective microstrip structure (DMS) and a rectangular resonator (RSR) on microstrip transmission lines. The primary focus of the article is to examine how the DMS-RSR structure can reduce crosstalk in microstrip transmission lines.

In the studies conducted by Zhang et al. [25], an examination is carried out on previous works, particularly the protective trace method by Huang et al. [15], the graphene-paraffin coating and protruding line structure found in the works of Cai et al. [23]. In this study, the authors evaluate their developed resonator structure by comparing it with these methods.

G. The effect of discontinuities in electronics and the importance of transitions

Especially in the transmission of high-frequency and fast signals, discontinuities can occur due to added ground plane transitions, threatening signal integrity. As a result of these discontinuities, undesired consequences such as reflections, signal loss, and electromagnetic interference may arise. In this context, various strategies have been developed to minimize the adverse effects of ground plane irregularities and ensure reliable signal transmission. Specifically, methods such as placing copper traces in a balanced manner, strategically positioning transition boundaries close to the ground plane, and using dielectric materials that offer lower loss in the transmission of high-frequency signals can help overcome these issues.

In the design of electronic circuit boards, the placement forms and locations of transitions are of critical importance. Park et al. [26] have conducted significant research on this subject. In their study, they evaluated the effects of distances between transitions using vertical and hexagonal transition vias on crosstalk. This study addresses one of the critical aspects of design, aiming to reduce crosstalk on electronic circuit boards and maintain signal integrity.

Shim and Oh [27], in their studies, introduced a different perspective on placing transitions with a structure they named "dogbone." This new idea has provided solutions for more effective and efficient placement of transitions, showcasing the potential of innovative approaches in the design of electronic circuit boards. Researchers like Park et al. [26] and Shim and Oh [27] have contributed to advancements in this field, leading to more efficient and reliable designs.

In his study, Lee [28] thoroughly examines the design of a meander split power/ground plane. Employs a distinctive approach to mitigate crosstalk occurring in the reference plane by introducing meander-shaped curves to the existing plane structure. These curved structures assist in controlling electromagnetic interactions when transmission lines traverse over them. The meander split power/ground plane structure aims to effectively suppress crosstalk by increasing electromagnetic coupling between transmission lines.

The return path is the circular path that the electric current completes by returning to its source. Xiao et al. [29] aim to comprehensively investigate the electromagnetic interference caused by discontinuities in the return path, particularly encountered in printed circuit boards. Xiao et al. [29] emphasize a solution approach in their study that involves adding discontinuity seam capacitance in the segmented reference plane to suppress electromagnetic interference.

The design, production, and improvement of electrical connections between different layers of printed circuit boards are of great importance. Traditionally, interlayer transitions are designed and produced vertically. However, the study conducted by Wang et al. [30] examines the impact of designing these transitions at a 45-degree angle on crosstalk issues. This study evaluates the potential advantages of a new approach in the design of electronic circuit boards and provides significant information that can benefit the industry.

II. RESEARCH FINDINGS AND EXPERIMENTAL RESULT

This section addresses strategies for mitigating the issue of crosstalk, which is a prominent problem within the complexities of electronic circuit design. In the process of developing electronic circuits, the crosstalk issue holds significant importance. Solution strategies developed for the crosstalk issue is thoroughly examined. In this context, the effects of transition barriers and integrated pin areas on crosstalk are specifically addressed with emphasis. Subheadings in this study also cover the impact of the fundamental parameters of the transmission line on crosstalk.

TABLE I
FREQUENCY BASED CHANGES IN CROSSTALK WITH DESIGN METHODS

Methods	F(GHz)	Crosstalk(dB)
DMS-RSR	3.2	-16
Non uniform line design	3.8	-48

A. Reducing crosstalk with design methods

Zhang et al. [25] and Almalkawi et al. [20], in their studies, examine the impact of design methods and reduction techniques to overcome the issue of crosstalk in electronic circuits. In these noteworthy works, the potential effects of crosstalk are particularly addressed within specific frequency ranges, and detailed information on the suppressions occurring at these frequencies is presented in Table I.

Zhang et al. [25] and Almalkawi et al. [20], along with their proposed structures, compare approaches based on different methods within the study. They successfully convey changes in crosstalk depending on different methods to the reader through clear graphics. Additionally, they enrich their studies by presenting structures related to different designs.

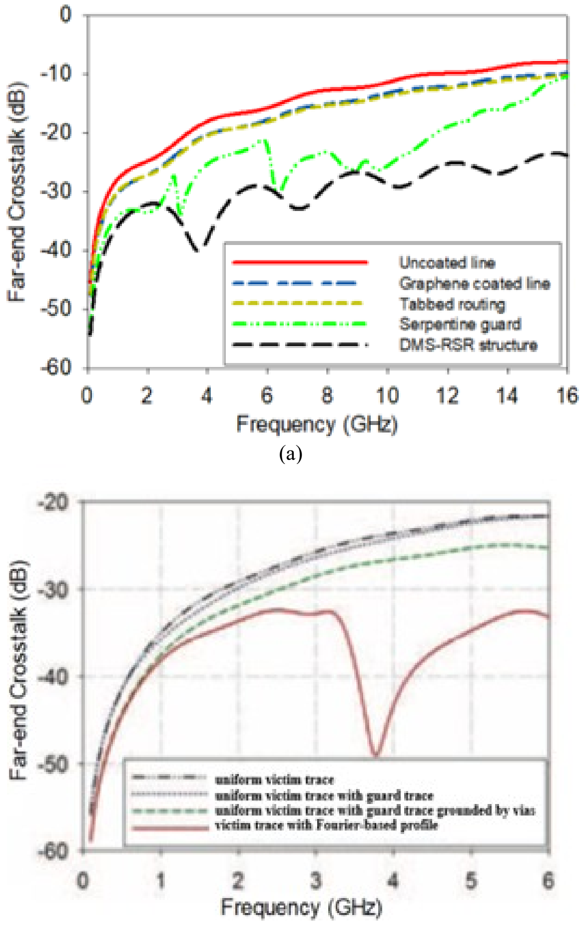
Zhang et al.'s [25] study encompasses content comparing four different methods. This comparison focuses on graphene-coated transmission lines, transmission lines, transmission lines with curved guard traces, and DMS-RSR structures.

Almalkawi et al. [20], four different designs were examined and compared. The compared transmission lines include those without smooth traces and guard traces, those with smooth traces and guard traces, those connected to the ground plane with vias and having Fourier-based profiles with guard traces, and those without guard traces.

In previous paragraphs, a general overview of the structures examined in the studies of both Zhang et al. [25] and Almalkawi et al. [20] has been provided. Now, we will focus on more detailed information regarding the comparisons between these structures. To better understand the comparisons between these structures, we can examine the visuals presented in Fig. 1. It clearly illustrates the effects of the compared different design methods on crosstalk.

The crosstalk in transmission lines with traditional unprocessed, graphene-coated, protruded, folded shielded, and DMS-RSR applied design methods are compared in Fig. 1(a), where it is observed that the DMS-RSR structure notably outperforms the others.

In Fig. 1(b), variations in the crosstalk of transmission lines with smooth and unshielded, smooth and shielded, shielded with vias connected to the ground plane, and Fourier-based profile with unshielded configurations are highlighted. It is noteworthy that the transmission line with a Fourier-based profile and no shielding is particularly more effective at a specific frequency compared to other methods.



(a)

(b)

Fig. 1. Examining different design methods. (a) Various design methods in Zhang et al.'s study [25] (b) Various design methods in Almalkawi et al.'s study [20]

B. Reducing crosstalk with production methods

Yu et al. [17] and Cai et al. [18] studies have focused on methods to reduce crosstalk through production techniques. How design methods affect values at similar frequencies are shown in Table II.

TABLE II
FREQUENCY BASED CHANGES IN CROSSTALK WITH PRODUCTION METHODS

Methods	F(GHz)	Crosstalk(dB)
Soldermask coated lines	3.2	-23
	16	-36
Coverlay coated lines	3.8	-48
	16	-40

The study by Yu et al. [17] examined the effects of coating transmission lines with solder mask or paint. Simultaneously, they observed the effects of painting the area between the transmission lines with solder mask to cover the transmission lines. In Fig. 2, the structure of a transmission line with a traditional solder mask is shown, and in Fig. 3, the structure where the area between the transmission lines is filled with solder mask is illustrated. Crosstalk simulation results for these structures are provided in Fig. 4 and Fig. 5, respectively. Shown in the figure, H1 is the solder mask thickness on the transmission line, H2 is the solder mask height on the PCB surface, H is the total thickness of the solder mask, and W is the width at which the soldermask maintains its height above the transmission line. Additionally, prepreg is a material used as an insulation material here.

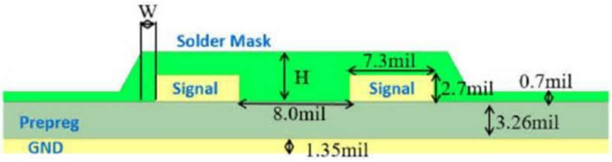


Fig. 2. Traditional solder mask application [17]

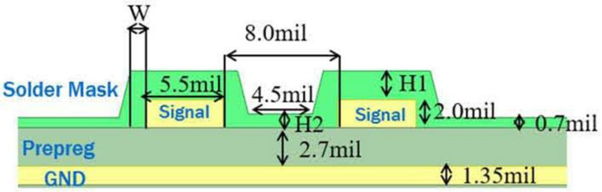


Fig. 3. Application of filling the space between transmission lines with solder mask [17]

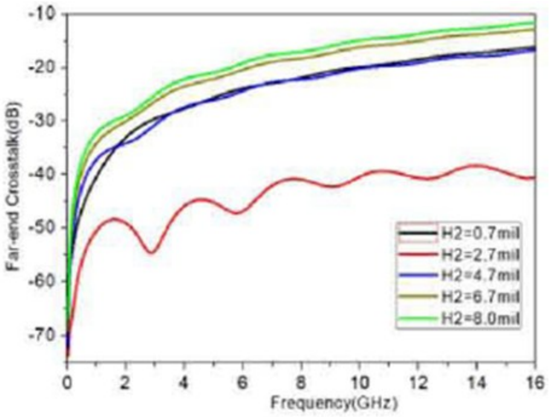


Fig. 4. The traditional structure with solder mask, The crosstalk varies with varying H2, with H1=6mil and W=1mil [17]

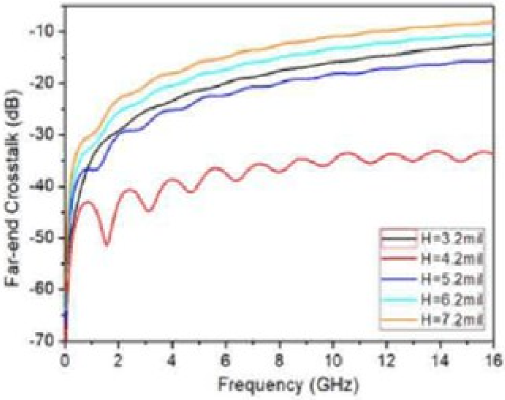
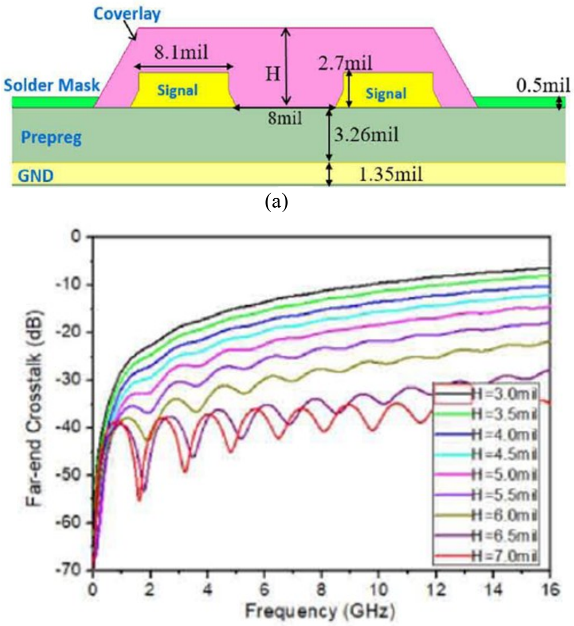


Fig. 5. Crosstalk in the proposed solder mask structure. Varying H, with W=0.5mil [17]

Cai et al. [18] investigated how far-end crosstalk changes when applying coverlay coating to a transmission line modeled in a traditional structure. Fig. 6 shows the structure of the proposed transmission line and the effects of cover height on far-end crosstalk. These graphs visually express the results of these critical parameters that affect the performance of transmission lines.

Fig. 6 shows the structure of the proposed transmission line and the far-end crosstalk associated with three key variables, including shroud height, dielectric constant, and dissipation factor. These graphs visually express the results of these critical parameters that affect the performance of transmission lines.



(a)

(b)

Fig. 6. The effects of coverlay coating application in the proposed structure on far-end crosstalk. (a) Application of coverlay coating to the proposed transmission line model; (b) FEXT at different H values, DK=3.5, DF=0.02, W=1mil [18]

C. Reducing crosstalk through the integration of design and production methods

The study by Cai et al. [23], protruded line designs were combined with a method that incorporated graphene paraffin material. In this study, protruded line design and graphene paraffin material were used as a combination of two different methods. Far-end crosstalk simulations conducted between the case where protruded line design was applied and the case where graphene paraffin material was used showed that the results were close. However, in both cases, it was determined that the crosstalk decreased by 12 dB at a frequency of 3.2 GHz according to simulation results.

In Fig. 7, it can be observed that the study conducted by Cai et al. [23] compares four different scenarios. In Scenario A, neither protrusions nor graphene-paraffin coating is present on the transmission lines. In Scenario B, there are no protrusions, but graphene-paraffin coating is applied. In Scenario C, protrusions are present, but no coating is applied. Finally, in Scenario D, both protrusions and graphene-paraffin coating are used.

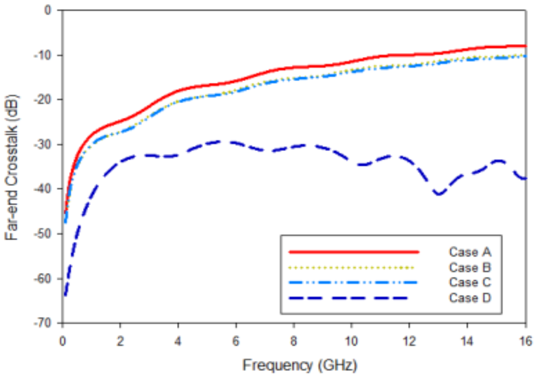


Fig. 7. The Effects of Protrusions and Graphene-Paraffin Coating [23]

D. *Reducing crosstalk due to the discrete structure of the reference plane*

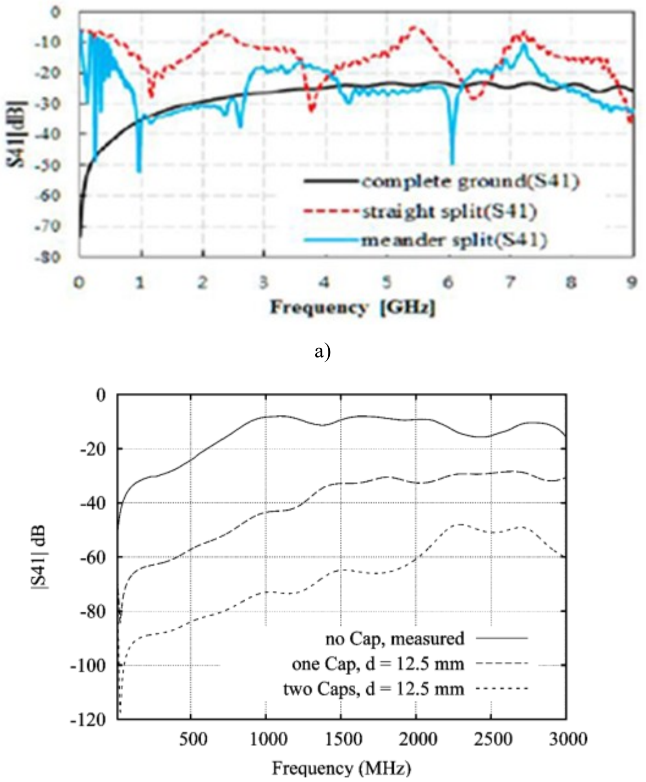
Lee [28] conducted research aimed at reducing crosstalk by adding a curved structure at the intersection points of the signal surface with the discrete structures on the reference plane. This approach stands out as a step to manage electromagnetic interactions and minimize unwanted signal crosstalk. On the other hand, in the study by Xiao et al. [29], the focus was on the results obtained by adding stitch capacitance to the intersection points of discrete regions with the signal surface. This approach also emerges as a notable alternative among crosstalk reduction strategies.

Table III provides a detailed presentation of the effects of these two different approaches on crosstalk depending on frequencies. Observing how both methods affect crosstalk in specific frequency ranges provides crucial information for the design. In the stitch capacitance method, experiments were carried out to examine the distance (d) between the transmission line and the loop capacity and the effects of different capacitance values. Table III contains the results where the maximum efficiency was achieved.

TABLE III
EFFECT OF DISCRETE STRUCTURE IN THE REFERENCE PLANE ON CROSSTALK

Methods	F(GHz)	Crosstalk(dB)
Meandering power-ground split plane	0-9	-30
Stitching capacitor design	0-3	-70

Fig. 8 shows the effects of the implementations by Lee [28] and Xiao et al. [29] on near-end and far-end crosstalk covering the specified frequency range.



a)

(b)

Fig. 8. Effect of discrete reference planes on crosstalk. (a) fext for discrete planes with different geometric structures [28] (b) stitch capacity [29]

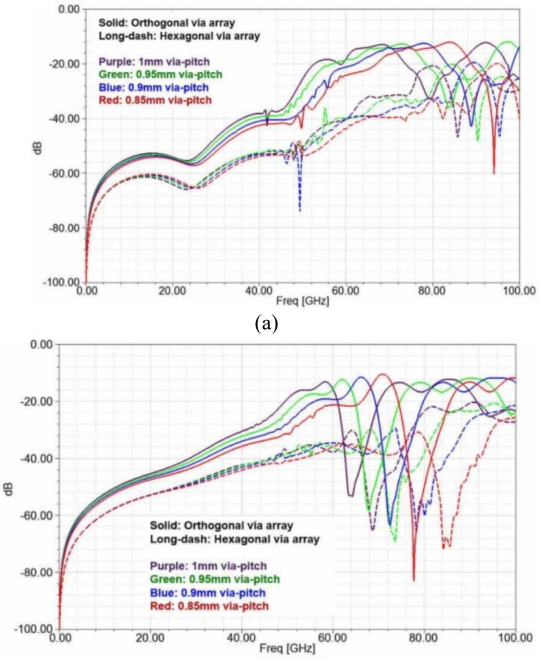
E. *The effect of transition and modifications in the integrated leg structure on crosstalk*

Park et al. [26] conducted research on the effects of the vertical and hexagonal transition fence structures on crosstalk depending on frequency. Shim and Oh [27], in their study, investigated the impact of a transition structure they named "dog bone." The effects of both methods are provided in Table IV.

TABLE IV
EFFECT OF TRANSITION FENCES AND INTEGRATED LEG STRUCTURE ON CROSSTALK

Methods	F(GHz)	Crosstalk(dB)
Vetical and hexagonal transition fences	0-8	-12
Dogbone structure	0-10	-10, -15

Fig. 9 presents the changes in crosstalk from Park et al.'s [26] study. Additionally, the relationship between crosstalk values and the distances from the center to center of the transitions is given for orthogonal and hexagonal transition arrays. This method reveals the importance of via arrays. The distances between inserted via arrays and the geometries they form together have a significant impact on the crosstalk.

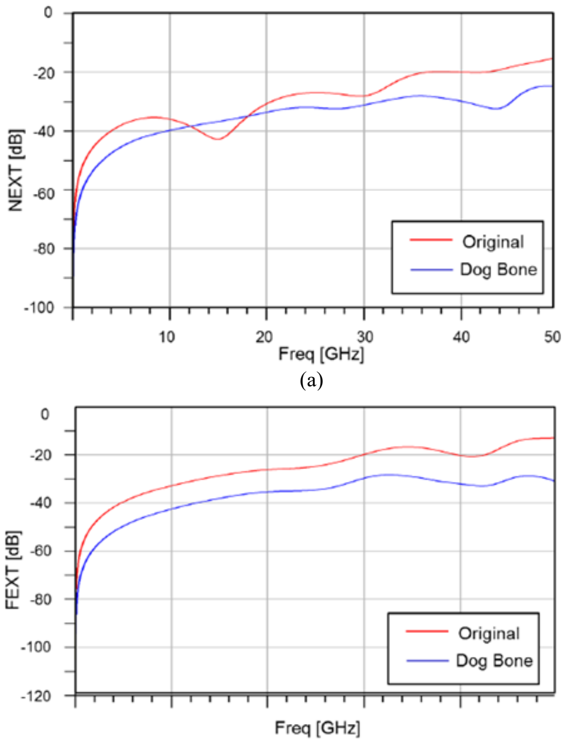


(a)

(b)

Fig. 9. The effects of orthogonal and hexagonal transition fences on crosstalk. (a) NEXT (b) FEXT [26]

Fig. 10 depicts the placement planning of transitions in the dog bone structure as considered in the study by Shim and Oh [27], along with their effects up to 50 GHz. This name was given because the geometry that emerged after the settlement resembles a dog bone. The desired result after placement is to ensure that the magnetic fields to be formed are perpendicular to each other. This perspective brings a different perspective and suggestion to via array layout.



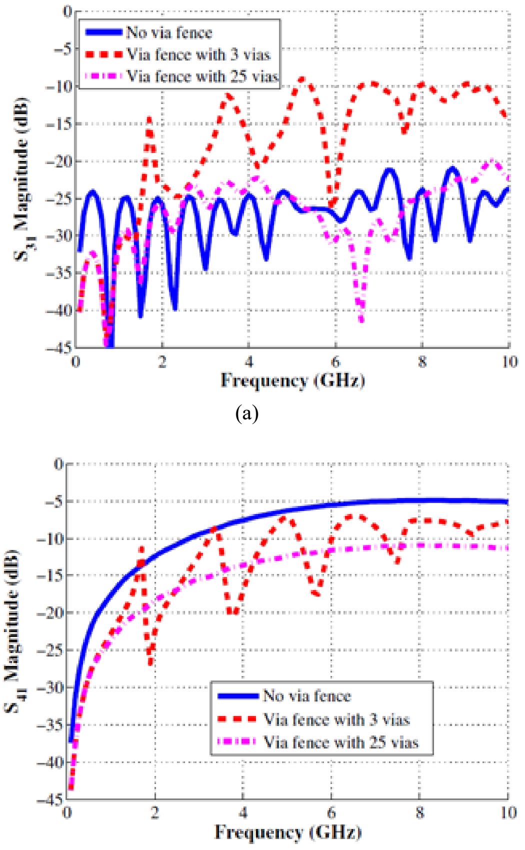
(a)

(b)

Fig. 10. Transition placement in dog bone structure and the effects of transitions on crosstalk. (a) NEXT (b) FEXT [27]

The study presented by Suntives et al. [19] extensively examines the effects of transition traces on near-end and far-end crosstalk in transmission lines. This research particularly focuses on the impact of the distances between transitions on the protective traces and the number of transitions along the transmission line on such types of crosstalk. Protective traces are added between transmission lines. Additionally, transitional structures were placed on this trace.

Fig. 11, Suntives et al. [19] presents the results of his study in the 0-10 GHz band. It also shows the effects of number of passes on far-end crosstalk. These graphs illustrate the results obtained for near-end and far-end crosstalk across the frequency range and compare simulation results with actual measurement outcomes. This visual representation serves as a crucial tool to convey the findings of the study in a more explicit and understandable manner. St shown here represents the distance between transmission lines.



(a)

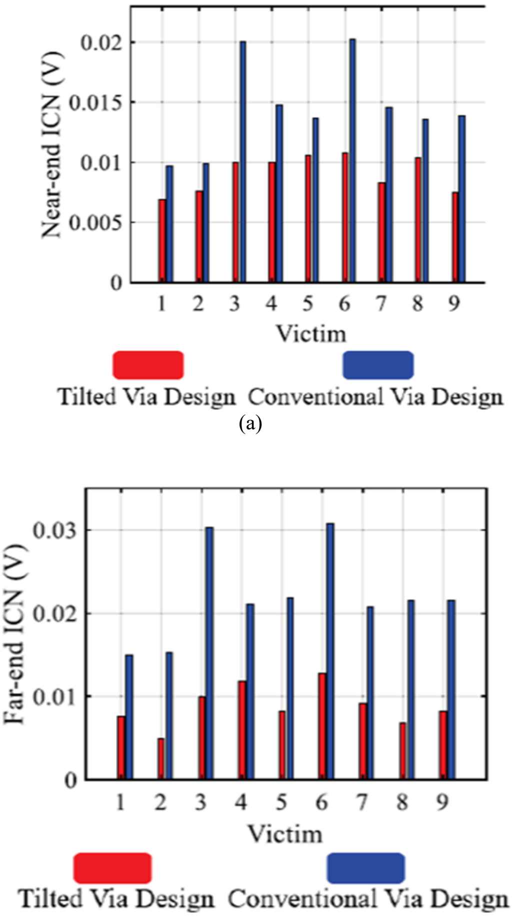
(b)

Fig. 11. Examination of the Effects of the Recommended Transmission Line Structure and the Number of Transition Fences on Crosstalk. (a) NEXT (b) FEXT [19]

The study presented by Wang et al. [30] highlights the positive effects of the integrated leg structure design on crosstalk. Specifically, the need to add a series of transitions under the integrated pins in the ball grid array (BGA) configuration used to route transmission lines in electronic circuits should be considered. In traditional electronic circuits, these transitions are typically characterized by 90-degree turns. However, the structure proposed in the study by Wang et al. [30] examines an approach involving 45-degree turns as an alternative to these 90-degree transitions. This new structure aims to reduce near-end and far-end crosstalk and seeks to achieve more favorable results compared to traditional 90-

degree transitions. By introducing a novel approach in electronic circuit design, this study evaluates the impact of the integrated leg structure on crosstalk, offering a significant contribution for future electronic circuit designs.

Fig. 12 illustrates the near-end and far-end crosstalk of the slanted via structure, which is the focal point of the study conducted by Wang et al. [30]. This graphic concretely presents the key findings of the study, highlighting the effects of the slanted via structure on transmission lines.



(a)

(b)

Fig. 12. The evaluation of the proposed slanted transition structure and its effects on crosstalk is presented. (a) NEXT and (b) FEXT) [30]

III. DISCUSSION AND CONCLUSION

Huang et al.'s [15] study focuses on adding a curved guard trace between two microstrip lines and how this trace is connected to transitions and the ground plane. On the other hand, Zhang et al. [25] explore a similar curved guard trace structure as mentioned in the Huang et al. [15] paper. However, it exhibits a different behavior due to its geometric structure. Both studies demonstrate that the proposed guard structures are effective in reducing crosstalk. However, using these structures in electronic circuit boards with high interconnects may not be feasible due to space constraints. These methods are more suitable for circuits with appropriate dimensions and a low number of interconnects. In the approach proposed by Zhang et al. [25], the guard trace is connected to the ground through a perforated transition, providing a more efficient result compared to the method proposed in the Huang et al. [15] study. This highlights the importance of selecting appropriate design and application scenarios.

Yu et al.'s [17] paper focuses on the paint thickness to be applied during the production of microstrip lines. On the other hand, in the study by Cai et al. [18], the microstrip line is covered with a shield instead of paint. While both methods are effective in reducing crosstalk, they come with challenges in production and an increase in costs. The paint used in the Yu et al. [17] study involves a situation where the height of the trace is different from the height at the edges. Therefore, an impedance calculator that takes these parameters into account is necessary.

The four studies you have evaluated stand out with different design approaches. For instance, in cases where circuit dimensions are more crucial, the methods employed in the studies by Yu et al. [17] and Cai et al. [18] might be preferable as cost increase takes a secondary role. On the other hand, in situations where circuit dimensions are less critical, and cost increase is not desired, following the approaches discussed in the papers by Huang et al. [15] and Zhang et al. [25] could be more appropriate.

The structures found in advanced electronic circuit boards have different power sources. The reference layers allocated for power planes are divided due to the presence of different blocks, leading to split structures. The studies by Lee et al. [28] and Xiao et al. [29] present two different approaches for these split structures. Each method has its own advantages and disadvantages. The curved structure highlighted in the Lee et al. [28] study performed well depending on the dimensions of the geometric shape created in the simulation environment. However, during the production of electronic circuit boards, variations in the width and length of traces can occur. Therefore, the current state of the produced circuit board requires these tests to be experienced in the real environment. However, intervention in this structure may not be possible after factors such as production errors or tolerances.

In the research investigated by Xiao et al. [29], the value of the utilized stitching capacity can be updated to subject the electronic circuit board obtained after production to crosstalk tests. This method provides flexibility for designers to intervene later. However, determining the location of this stitching capacity, allocating appropriate space on the circuit board, and minimizing material-related tolerance errors are necessary. In this way, a better balance can be achieved between the performance of the board and crosstalk reduction strategies.

In the study conducted by Suntives et al. [19], the number and location of transitions were thoroughly examined for their effects on transmission lines. The results highlight the differences between scenarios with no transitions and those with three transitions. In this context, an increase of approximately 17 dB in near-end crosstalk was observed, indicating adverse effects under these conditions. Additionally, it was found that these conditions resulted in worse outcomes rather than improvements across almost all examined frequency ranges. On the other hand, in the scenario with 25 transitions, the opposite was observed. In these conditions, both near-end crosstalk and far-end crosstalk decreased across almost all frequencies. It was determined that near-end crosstalk decreased by approximately 17 dB, and far-end crosstalk decreased by approximately 8 dB. These results demonstrate the critical importance of the number and location of transitions in the design of transmission lines and guard traces. The study presented by Suntives et al. [19] contributes to engineers making better design decisions to enhance transmission line performance and reduce electromagnetic compatibility issues. It is important to validate the simulation results obtained in these studies with measurement devices on real electronic circuits.

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