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Yokesh V. On the Design of a Stepped Mixed Signal Transmission Line with Defected Microstrip Structure for High-Frequency PCB Traces. *JOURNAL OF HIGH-FREQUENCY COMMUNICATION TECHNOLOGIES*, 2024, 2 (01), pp.120-129. 10.58399/RZRQ1838 . hal-04476778

HAL Id: hal-04476778

<https://hal.science/hal-04476778>

Submitted on 25 Feb 2024

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On the Design of a Stepped Mixed Signal Transmission Line with Defected Microstrip Structure for High-Frequency PCB Traces

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Abstract

The paper addresses the challenge of crosstalk in neighboring paths on PCBs, emphasizing its growing importance with the advancement of electronic circuits in terms of speed and frequency. The proposed solution involves the introduction of a novel W-shaped defected microstrip structure (DMS) on a step-shaped-coupled transmission lines to mitigate near-end crosstalk (NEXT) and far-end crosstalk (FEXT) using mixed signal input. A novel W-shaped DMS that is etched on step shaped-coupled transmission lines. The proposed technique focuses on minimizing the electromagnetic coupling strength with a minimum spacing of one time the width of the trace. It optimizes the ratio of capacitive coupling and inductive coupling between the coupled microstrip transmission lines to improve crosstalk. The frequency domain simulation, conducted using Computer Simulation Technology (CST), indicates promising results. The insertion loss ($|S_{21}|$), near-end crosstalk ($|S_{31}|$), and far-end crosstalk ($|S_{41}|$) of the suggested structure are reported as 1.425 dB, <25 dB, and <25 dB, respectively, over the frequency range of 0 to 10 GHz. Eye diagram characterizations are done and measured in terms of eye height, eye width, jitter and data rate are reported as 0.942 V, 695.5 ps, 6.69 ps and 1.4 Gbps, respectively.

Keywords: Defected Microstrip Structures, FEXT, NEXT, Mixed signals

1. Introduction

The pervasive integration of electronic components, propelled by rapid advancements in industrial technology and the escalating demand for electronic devices, has underscored the pivotal role of integrated circuits (ICs) in modern electronics (Dmj and Sm, 2020). However, the formidable impediment of crosstalk, induced by coupling effects within transmission lines—a critical interconnect structure in ICs—has arisen as a substantial obstacle to the unabated progression of these circuits. In response to the imperative for higher circuit integration, the spatial constraints between microstrip lines have become markedly diminished. This reduction in spacing, although essential for meeting the stringent integration requirements, concurrently exacerbates the susceptibility to coupling crosstalk among microstrip lines (Mudavath et al., 2019). This predicament necessitates a concerted effort from the research and engineering communities to devise effective strategies for mitigating crosstalk; thereby, aligning with the trajectory of integrated circuit development. As researchers and engineers collectively endeavor to surmount these challenges, innovations in crosstalk reduction techniques are anticipated to play a pivotal role in sustaining the momentum

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Received: 14th, December 2023, Revised: 04th February, 2024, Accepted: 15th February 2024 and available online 25th February 2024



of integrated circuit advancements. In adherence to the tenets governing crosstalk (Tsou et al., 2018), a thorough examination reveals that enlarging the spacing between transmission lines serves as a successful method to improve crosstalk performance. The impact of this enhancement is precisely analyzed through electromagnetic (EM) simulations, incorporating the tactical placement of a via-stitch guard or a serpentine guard trace between transmission lines (Che et al., 2019), (Balakrishnan et al., 2018) & (Packianathan and Arumugam, 2020). However, the practical implementation of such solutions encounters challenges attributable to the intricate nature of their structures, coupled with potential resonance issues. In an alternative approach, the application of graphene-based coatings to microstrip transmission lines emerges as a countermeasure to crosstalk (Refaie et al., 2018). Although this method exhibits promise, it increases the manufacturing cost owing to the deposition of graphene. Moreover, the coating absorbs a certain amount of transmission power, thereby presenting an additional drawback. The researchers, in pursuit of crosstalk reduction, probe into the alteration of the physical structure of transmission lines (Firdous and Gupta, 2012), (Kazerooni et al., 2012) & (Liu et al., 2018). This method aims to modify the ratio of inductive to capacitive coupling; thereby, reducing crosstalk. However, this approach has its limitations, as the far-end crosstalk enhancement remains less than ideal. Notably, certain stepped structures (Zhang et al., 2019) manifest a maximum enhancement of up to 6 dB, indicative of partial efficacy in mitigating crosstalk. These nuanced challenges underscore the ongoing quest for refined methodologies to optimize the reduction of crosstalk in the realm of integrated circuit design. In the realm of mitigating electromagnetic interference between closely spaced high-frequency transmission lines, the employment of guard traces has been explored in (Yokesh et al., 2023). Notably, the utilization of cross-shaped resonators in conjunction with via fences serves as an innovative approach to act as guard traces, effectively addressing near-end and far-end crosstalk in tightly coupled high-speed transmission lines. The prescribed strategy involves maintaining a fixed spacing between traces exceeding one times the width of the transmission line, particularly within the frequency range up to 5 GHz. This intentional spacing is crucial for optimizing the performance of the guard traces in suppressing crosstalk effects. The state of the art comparison table is shown in Table 1.

Table 1. State of the Art Comparison

Proposed		(Li et al., 2021)	(Zhang et al., 2019)	(Liu et al., 2018)
Length of Microstrip line	50 mm	32 mm	10 mm	12.8 mm
Substrate Material	Rogers	FR4	FR4	FR4
Substrate Thickness	1.6 mm	1.6 mm	0.10 mm	3 mm
Spacing between the Transmission Line	1 W	2 w	2W	1W
Frequency	0-10 GHz	1-8 GHz	1-16 GHz	1-12 GHz
Insertion Loss - S21	1.425dB	Not Measured	Not Measured	Not Calculated
Near End Crosstalk - S13	25.52dB	Not Measured	Not Measured	Nearly 30dB
Far End Crosstalk - S14	25.35dB	Less than 20dB	Less than 25dB	Nearly 30dB
Characteristics Impedance	50Ω	50Ω	50Ω	50Ω
Signal Transmission	Mixed	Analog	Analog	Analog

Based on the findings from the aforementioned research, this paper advocates for the implementation of a W-shaped defected microstrip structure (DMS) characterized by its simplicity and a minimal spacing of 1W between transmission lines. In the frequency spectrum spanning from DC to 10 GHz, the introduction of the W-shaped DMS yields notable improvements in insertion loss, near-end crosstalk, and far-end crosstalk. To rigorously assess the usefulness of this proposed method, comprehensive simulations are conducted utilizing the computer simulation technology (CST) studio suite. The full-wave simulations serve as a robust means of evaluating the perfor-

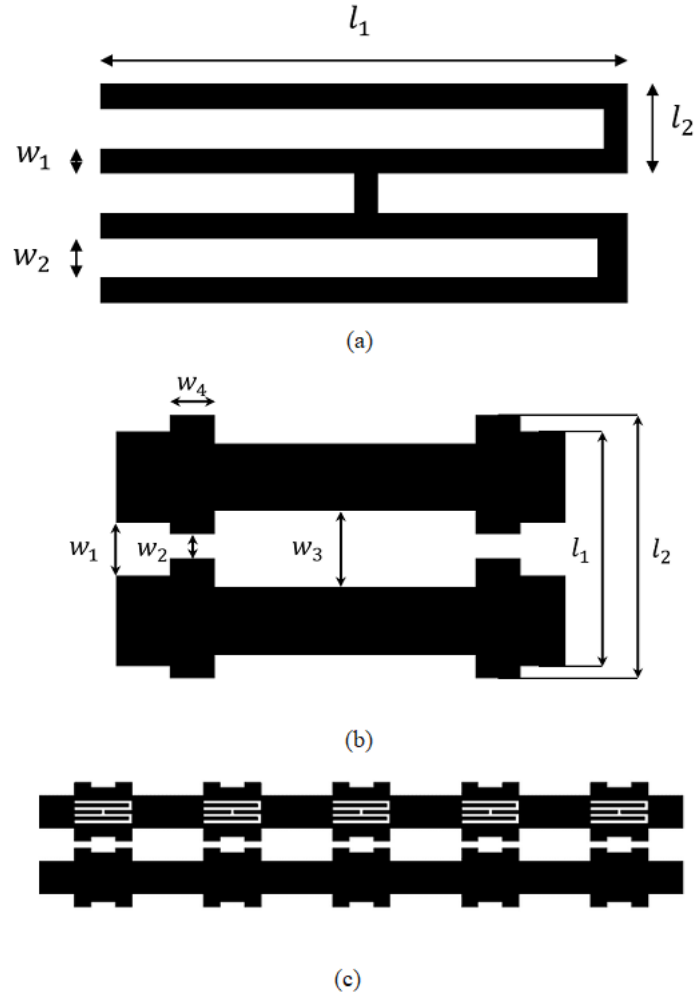


Figure 1. (a) Proposed DMS structure (b) Proposed Step-shaped transmission lines (c) Step-shaped transmission lines loaded with DMS

mance of the W-shaped DMS under diverse conditions. Notably, the measured results obtained experimentally align closely with the simulated outcomes, affirming the viability and utility of the method expounded in this paper. This research contribution signifies a practical advance towards addressing the challenges posed by crosstalk in integrated circuits, offering a simplified yet effective solution with the W-shaped DMS.

2. Design of Step Shaped Microstrip Transmission Lines

The intricate process of designing a DMS is underscored by the inherent complexity arising from alterations in the current path induced by the defects on the trace. To navigate these challenges, a novel approach is proposed, involving the combination of two U-shaped (or W-shaped) structures as the defected elements. This innovative configuration aims to enhance the performance of the DMS although addressing the complexities associated with the current path modifications. The DMS, in its proposed form, incorporates a composition of parallel and perpendicular slots strategically implemented in the aggressor transmission line. This deliberate arrangement of slots serves as a means to disrupt unwanted electromagnetic interactions, specifically addressing Near-End Crosstalk (NEXT) and Far-End Crosstalk (FEXT). Significantly, this is achieved without compromising the insertion loss, a critical consideration in maintaining signal integrity.

To optimize the functionality of the DMS, the construction of these defected structures is

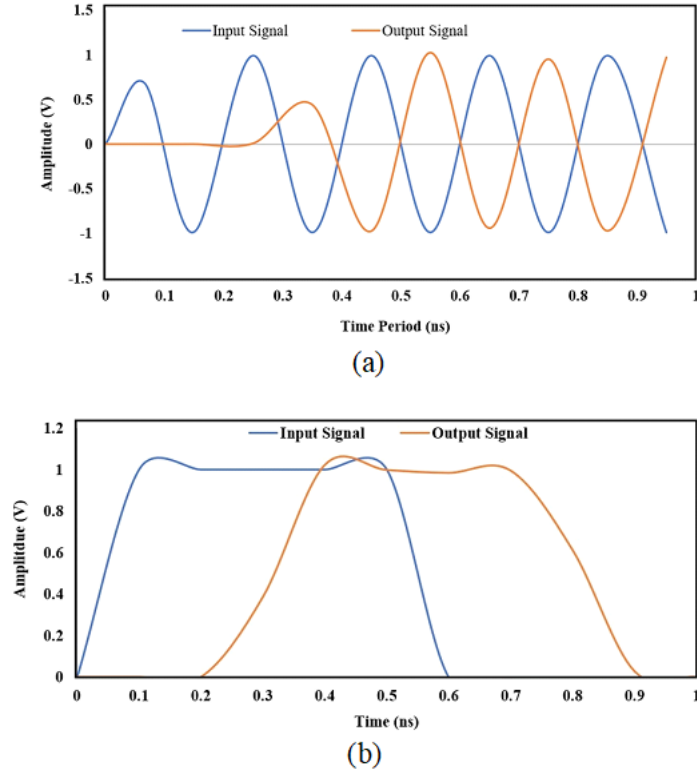


Figure 2. (a) Analog Signals (b) Digital Signals

periodically repeated along the step-shaped transmission line. This periodic repetition contributes to the alleviation of the impact of both NEXT and FEXT, ensuring a more robust and reliable performance across the desired frequency range of 0 to 10 GHz. The overarching goal of this design is to attain a broader frequency bandwidth, enhancing the versatility of the DMS in addressing signal integrity challenges. The careful consideration of both structure and periodic repetition underscores the nuanced and thoughtful approach taken in the pursuit of an effective and efficient DMS.

Equation 1 gives the crosstalk voltage that is induced at any place on the victim line that is linked to another line that is driven by a signal $V_{in}(t)$ at any given time.

$$V = K_f x \frac{d}{dt} V_{in} \left(t - T_d \frac{x}{L} \right) + K_b \left[V_{in} \left(t - T_d \frac{x}{L} \right) - V_{in} \left(t - 2T_d + T_d \frac{x}{L} \right) \right] \quad (1)$$

where K_f and K_b are the forward (FEXT) and backward (NEXT) crosstalk coefficients, respectively, expressed in terms of the ratios of mutual inductance to self-inductance (L_m/L) and mutual capacitance to self-capacitance (C_m/C) as shown in Equ. 2 and 3.

$$K_f = -\frac{1}{2v} \left(\frac{L_m}{L} - \frac{C_m}{C} \right) \quad (2)$$

$$K_b = \frac{1}{4} \left(\frac{L_m}{L} + \frac{C_m}{C} \right) \quad (3)$$

where v is the propagation velocity (speed) of the signal on the line. The proposed model introduces a dual U-shaped DMS topology, etched on to the aggressor line, as illustrated in Figure 1. This configuration leverages the strategic manipulation of the distance between microstrip lines, thereby influencing the electric field strength and, consequently, the magnitude of capacitive coupling. Notably, the proximal segment of the microstrip line exhibits a larger capacitive coupling, whereas the distal portion experiences a reduced capacitive coupling. This dynamic distribution effectively

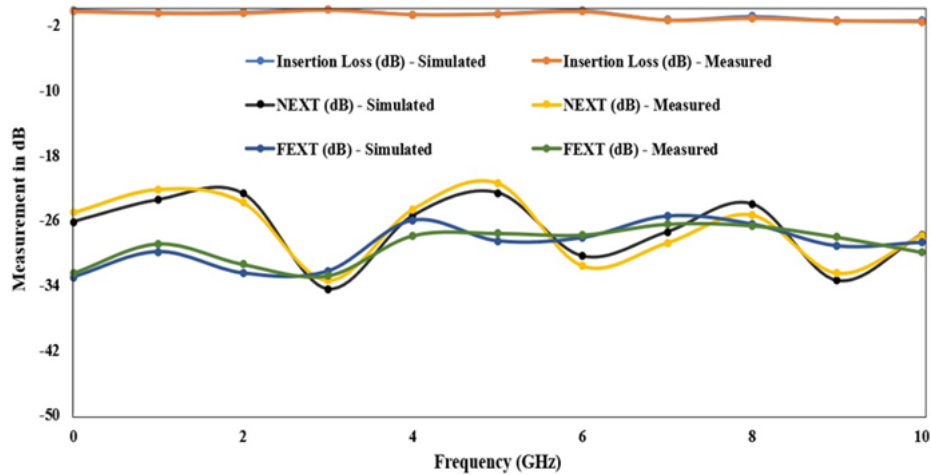


Figure 3. Scattering Parameters of Insertion Loss ($|S_{21}|$), Near-End Crosstalk ($|S_{31}|$), Far-End Crosstalk ($|S_{41}|$) – Simulated Vs Measured

mitigates both near-end and far-end crosstalk, not only among transmission lines but also within the spatial confines between interconnected transmission lines. The validation and assessment of the proposed structure are conducted through meticulous modelling and simulation procedures, facilitated by Computer Simulation Technology (CST). To ensure the robustness and reliability of the findings, the results obtained from simulations are cross-verified using a Vector Network Analyzer (VNA). The effectiveness of the proposed structure is quantified through key metrics, including insertion loss ($|S_{21}|$), near-end crosstalk ($|S_{31}|$), and far-end crosstalk ($|S_{41}|$), revealing its proficiency in optimizing signal integrity and minimizing interference in the designated frequency range of 1 to 10 GHz. The dimensions of the proposed Step-shaped transmission with DMS is shown in Table 2.

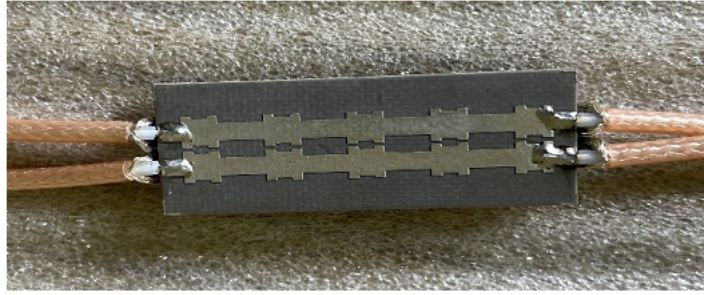
Table 2. Dimension Details of DMS and Step-Shaped

Parameters	Dimensions(mm)
l_1, l_2 -Lengths	7.6 & 6
w_1, w_2, w_3, w_4 -Spacing	1, 0.2, 2 & 1
l -Length of transmission line	40
w -Width of transmission line	2
s -Spacing between the transmission line	2
h -Height of dielectric substrate	1.6
n -Number of defective structures on the transmission line	5
ϵ_r -Dielectric Constant	2.2

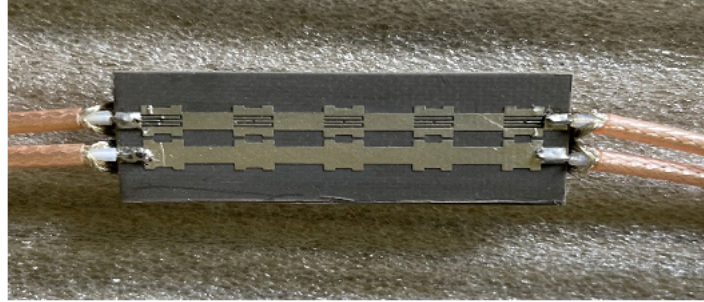
3. Simulation and Measurements

3.1. Input and Output Signals

Mixed Signals are preferred over analog signals due to greater degree of flexibility, enabling high precision and accuracy, reduced sensitivity to environmental factors, improved signal-to-noise ratio (SNR) and less susceptible to signal degradation over long distances. In the design of the



(a)



(b)

Figure 4. Fabricated Structure (a) Without DMS (b) With DMS

step-shaped transmission line with a slot pattern, mixed signals, encompassing both analog and digital inputs, are introduced. Figure 2 (a) illustrates the analog input as a sinusoidal signal characterized by a frequency of 5 GHz and a peak-to-peak amplitude of 2V. This sinusoidal analog signal serves as a representative input, capturing the continuous and varying nature of analog waveforms. Upon traversing the designed transmission line, the signals at the output port exhibit distinctive characteristics. Specifically, the received sinusoidal signals manifest a delay of 0.22 ns, indicating a temporal shift introduced during transmission. Furthermore, the peak-to-peak amplitude of the received signals is measured at 1.95V, suggesting a nominal reduction in amplitude likely influenced by the transmission line characteristics and inherent signal processing effects. In Figure 2 (b), a rectangular pulse serves as the input to the transmission line, characterized by a rise time of 0.1 ns, a fall time of 0.1 ns, and a threshold time of 0.6 ns. The peak-to-peak amplitude of the rectangular pulse is specified to be 1V, representing a distinct digital signal with sharp transitions. The received signal exhibits a delay of 0.22 ns, indicating a temporal shift introduced during transmission. Notably, the peak-to-peak amplitude of the received rectangular pulse registers at 0.92V, denoting a reduction in amplitude when compared with the input signal.

An interesting observation is the mitigation of ringing effects in the received signal. The term "ringing effects" typically refers to unwanted oscillations or overshooting/undershooting phenomena that can occur in digital signals during transmission. The noted reduction in ringing effects suggests that the design of the transmission line, likely influenced by the integrated slot pattern, has been effective in minimizing these undesired transient behaviors.

3.2. Scattering Parameters

The simulated results are presented in Fig. 3, which offers a comprehensive insight into the performance of the microstrip line, comparing scenarios with and without the integration of DMS. The key parameters under examination include insertion loss ($|S_{21}|$), near-end crosstalk ($|S_{31}|$), and far-end crosstalk ($|S_{41}|$). The graph vividly illustrates the superiority of the microstrip line

loaded with DMS across all evaluated aspects. Notably, the insertion loss for the configuration incorporating DMS is consistently below 1.5 dB over the broad frequency range of 1 to 10 GHz, showcasing a commendable enhancement as compared to the microstrip line without DMS.

The near-end crosstalk (NEXT) exhibits a substantial improvement, with at least 5 dB enhancement observed for the DMS-laden structure as compared to its counterpart without DMS and the fabricated structure is shown in Fig. 4. This improvement is a testament to the efficacy of the DMS in minimizing interference between adjacent transmission lines. Similarly, in the context of far-end crosstalk (FEXT), the improvement is particularly noteworthy. Up to a frequency of 5 GHz, the with-DMS structure shows a gradual enhancement. However, as the frequency surpasses this threshold, a remarkable improvement of more than 20 dB becomes evident at 10 GHz compared with the structure without DMS. This underscores the effectiveness of the DMS in attenuating crosstalk effects, especially at higher frequencies.

In summary, the incorporation of DMS proves instrumental in enhancing the overall performance of the microstrip line, as evidenced by lower insertion loss and significant improvements in both near-end and far-end crosstalk across the evaluated frequency spectrum.

Table 3. Parameters of the Simulated Eye Diagrams of Step-Shaped Microstrip Transmission Lines

Parameters	Simulated		Measured With Defected Microstrip Structure
	Without Defected Microstrip Structure	With Defected Microstrip Structure	
Eye Amplitude	0.896 V	0.981 V	0.968 V
Eye Height	0.945 V	0.956 V	0.942 V
Eye Width	600 ps	600 ps	695.5 ps
Jitter	5 ps	5 ps	6.696 ps
Data Rate	2 Gbps	2 Gbps	1.4 Gbps

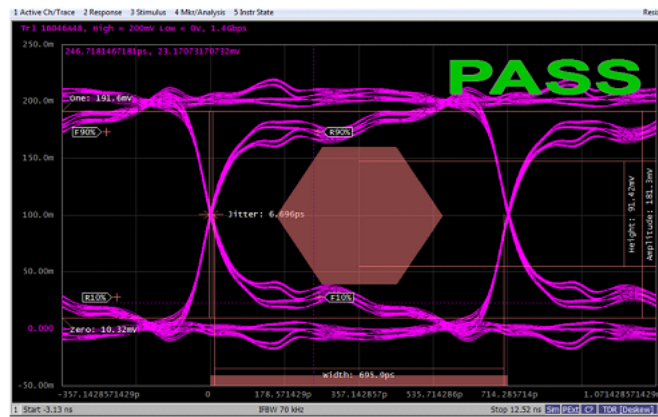
3.3. Eye Diagram Characterization

The eye diagram shown in Fig. 5 serves as a valuable representation of the time-domain analysis for the designed step-shaped transmission lines loaded with DMS. The analysis is conducted using a 2^7 Pseudo-Random Binary Sequence (PRBS) signal as the input, characterized by a rise time and fall time of 0.1 ns each. The observed eye diagram exhibits a commendable performance, with a wider opening indicating a well-defined and reliable signal reception. The amplitude of the eye is measured at 0.968 V, denoting the range of signal values within the eye diagram. Concurrently, the height of the eye, representing the vertical separation between the upper and lower signal levels, is recorded at 0.942 V. In terms of the data rate, the achieved value for the given input configuration is approximately 1.4 Gbps. This indicates the rate at which information is successfully transmitted through the designed system. Jitter, a crucial metric reflecting the deviation in signal timing, is quantified at 6.696 ps upon measurement. Jitter is a key consideration in high-speed data transmission, and the measured value suggests a relatively low level of temporal variation in signal timing.

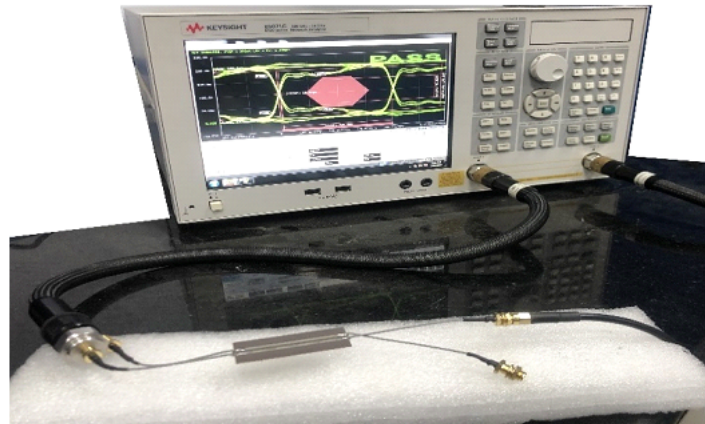
Table 3 consolidates the simulated vs measured values, providing a comprehensive overview of the eye diagram characteristics. The visual representation includes the eye amplitude, height, and width, along with the quantified jitter and the data rate. These metrics collectively affirm the robustness and reliability of the designed step-shaped transmission lines with DMS in accommodating high-speed data transmission, as evidenced by the well-defined eye diagram and the associated performance parameters.

3.4. Time Domain Reflectometry

The design of the proposed structure is tailored to achieve a characteristic impedance of 50Ω , as illustrated in Fig. 6. The simulated impedance, spanning the frequency range of 0 to 10 GHz, consistently maintains a value close to the targeted 50Ω . Small oscillations are observed within this frequency range, indicating the stability and effective impedance matching of the designed structure. Post-construction, the measured impedance aligns closely with the simulation results, demonstrating a characteristic impedance value of approximately 50Ω . This alignment underscores the success of the design implementation in achieving the intended impedance characteristics, which is a critical parameter in ensuring efficient signal transmission and minimizing reflections within the transmission line. The stability of the characteristic impedance over the designated frequency range is indicative of the robustness and precision in the design of the proposed structure. This conformity to the desired impedance profile enhances the compatibility of the structure with external components and contributes to the overall signal integrity of the transmission line.



(a)



(b)

Figure 5. Step-shaped microstrip transmission line (a) Measured eye diagram at 1.4 Gbps (b) Experimental setup for time domain analysis

4. Salient Features of the Proposed Method

The comparative analysis of the proposed DMS designs against similar studies in the literature reveals several noteworthy distinctions:

- The proposed works feature a longer length of the transmission line (40mm), particularly in

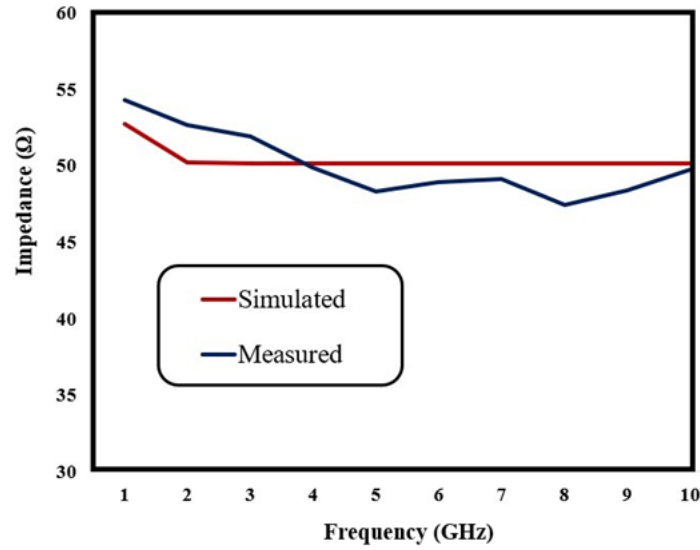


Figure 6. Impedance trace of DMS-based step-shaped transmission line

comparison to studies conducted by (Li et al., 2021), (Zhang et al., 2019) & (Liu et al., 2018). This extended length is a notable characteristic, especially in the context of high-frequency ranges.

- The insertion loss is 1.48 dB for Rogers substrate material in the design of DMS using CML and 1.425 dB for FR4 substrate material in the design of DMS using a step-shaped transmission line, respectively. In the literature, these values are not reported in the paper.
- The proposed DMS designs achieve NEXT values greater than 20 dB. This indicates a robust performance in mitigating near-end crosstalk (NEXT) effects, particularly within the specified frequency ranges of 1–10 GHz.
- This demonstrates a substantial reduction in FEXT values, especially for minimum spacing configurations of 1W between coupled microstrip transmission lines. This reduction is indicative of effective interference mitigation strategies employed in the proposed DMS designs.

5. Conclusions

The primary objective of this paper is to present an innovative approach for mitigating both near-end crosstalk (NEXT) and far-end crosstalk (FEXT) through the utilization of W-shaped step-shaped transmission lines, with a particular emphasis on minimizing the spacing between these transmission lines. The proposed method involves the incorporation of W-shaped DMS on to the aggressor line. Through a comprehensive examination that includes theoretical analysis, simulations, and practical measurements, the effectiveness of the W-shaped DMS in conjunction with the step-shaped transmission line is demonstrated. The achieved results showcase a notable improvement in insertion loss, with a specific reduction of 1.425 dB.

Furthermore, the impact on the crosstalk is particularly noteworthy. The near-end crosstalk of the transmission lines experiences an enhancement of approximately 20dB, indicating a substantial reduction in unwanted signal interference between closely spaced lines. Similarly, the far-end crosstalk improvement is remarkable, reaching up to 25 dB within the frequency range of 0 to 10 GHz. This enhancement signifies the efficacy of the proposed method in minimizing signal coupling effects at greater distances along the transmission lines.

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