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Metamaterial-Inspired Stub-Loaded EBG Structures for Broadband PDN Noise Mitigation in High-Speed PCBs

Aishwaryaa L K [1], *S. Chitra*[1], *R. Hema*[1*] *and M. Sundararajan*[1]
[1]Department of ECE, BIST, Bharath Institute of Higher Education and Research, Chennai, India

Abstract. Ultra-wideband (UWB) high-speed planar circuits suffer from power/ground noise due to voltage fluctuations, ground bounce, return-path discontinuities, and plane resonances, leading to electromagnetic interference (EMI) and signal integrity (SI) degradation. Suppressing simultaneous switching noise (SSN) is crucial for ensuring stable power delivery in high-speed printed circuit boards (PCBs). This study presents a metamaterial-inspired electromagnetic bandgap (EBG) structure aimed at mitigating broadband noise. The stub-loaded cross-shaped resonator (SLCSR) provides a peak noise suppression of –37 dB. Using cascaded and long-bridge SLCSR-based EBG designs further increases suppression to –47 dB and –52 dB, respectively. When vias are incorporated, the structure achieves up to –55 dB suppression across the ultra-wideband (UWB) spectrum. Experimental results from fabricated prototypes closely match the simulations, demonstrating the effectiveness of the proposed design.

1. Introduction

In general, the power distribution network (PDN) of a printed circuit board (PCB) consists of power and ground planes that supply energy to digital and analog components in high-speed systems. The primary objective of PDN design is to ensure stable power delivery by suppressing simultaneous switching noise (SSN), which is generated by rapid transient current variations within a short time interval. In high-speed systems, RF and analog circuits are highly sensitive to SSN, which can lead to severe signal integrity (SI) and power integrity (PI) degradation. Therefore, improving PI in high-speed systems necessitates the implementation of effective noise isolation structures [1–3]. Several techniques have been proposed to suppress SSN. One conventional approach involves placing decoupling capacitors between power planes; however, these capacitors exhibit dominant inductive behavior at microwave frequencies, limiting their effectiveness beyond sub-1 GHz and typically below 100 MHz [4].

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*Corresponding author: drhemarajamatha@gmail.com

Power island partitioning is another method, but it often introduces undesirable SI issues. Embedded parallel-plate capacitors with reduced dielectric thickness have also been explored [5,6], though their fabrication complexity and material requirements significantly increase cost.

To overcome these limitations, alternative PDN design techniques such as arrays of ground vias, split power planes, and power islands have been introduced. Although these methods can provide localized noise isolation, they typically achieve only narrowband suppression and lose effectiveness at gigahertz frequencies. With modern high-speed circuits increasingly operating in the GHz range, maintaining low PDN impedance across a wide bandwidth remains a major challenge.

To address this, metamaterial-inspired electromagnetic bandgap (EBG) structures have been extensively studied for broadband suppression of SSN and power/ground noise. These structures create periodic discontinuities that block electromagnetic wave propagation within defined stopbands. By incorporating stepped-impedance designs and high-impedance surfaces (HIS), metamaterial-inspired EBG structures can achieve wideband noise suppression, thereby substantially improving power integrity (PI) and signal integrity (SI) in high-speed digital and RF systems.

Recently, metamaterial-based EBG structures have been extensively employed in PCB PDNs to mitigate SSN by realizing high-impedance surfaces between power and ground planes [7–13]. Among various configurations, planar metamaterial-inspired EBG structures are particularly attractive due to their ease of fabrication and compatibility with multilayer PCB stack-ups. Typically, such structures consist of a patterned metamaterial plane paired with a continuous reference plane, forming a bandgap that suppresses noise propagation and electromagnetic interference (EMI).

In this paper, a novel metamaterial-inspired Stub-Loaded Cross-Shaped Resonator (SLCSR) EBG structure is proposed for broadband SSN suppression in high-speed PCB power distribution networks**.**

2. Design and Analysis of Metamaterial-Inspired SLCSR Structures

This section presents the design, simulation, fabrication, and experimental validation of a novel metamaterial-inspired Stub-Loaded Cross-Shaped Resonator (SLCSR) structure for mitigating simultaneous switching noise (SSN) in printed circuit boards (PCBs). The primary objective is to enhance broadband noise suppression across the ultra-wideband (UWB) frequency range of 0–12 GHz**.**

A systematic performance comparison is carried out among **a** basic square-shaped Cross-Shaped Resonator (CSR**)**, an enhanced stub-loaded CSR (SLCSR)**,** and three advanced metamaterial-based noise suppression configurations, namely cascaded SLCSR**,** long-bridge SLCSR, and long-bridge SLCSR with vias. Both electromagnetic simulations and experimental measurements are employed to validate the effectiveness of each configuration.

Base Metamaterial Unit-Cell Design

- **Substrate:** FR4
- **Unit-cell size:** 9 mm × 11.5 mm
- **Embedded region:** 50 mm × 50 mm
- **Substrate thickness:** 1.5 mm
- **Relative permittivity (εr):** 4.4

The proposed metamaterial-inspired resonator pattern is etched on one copper layer, incorporating slots and interdigital features, while the opposite layer remains a continuous metallic plane to realize high-impedance surface (HIS) behavior. This configuration enables effective suppression of guided electromagnetic noise waves within the PDN.

Noise excitation is introduced through a single-ended microstrip line**,** injecting test signals directly into the power plane to evaluate noise suppression performance. Prototypes were fabricated for all five configurations: basic CSR, SLCSR, cascaded SLCSR, long-bridge SLCSR, and long-bridge SLCSR with vias.

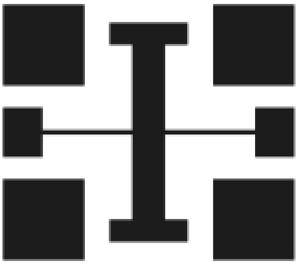

Fig 1 Square shape CSR EBG

Measurement Setup

Measurements were conducted using a Vector Network Analyzer (VNA) (Keysight PNA series or equivalent) to obtain accurate S-parameters. SMA connectors were soldered onto the test boards to ensure reliable signal injection and minimal impedance mismatch.All measurements were performed over the 0–12 GHz UWB frequency range.

Methodology Overview

The overall methodology consists of three stages:

- **Step 1:** Design of an efficient metamaterial-inspired resonator structure
- **Step 2:** Etching of the metamaterial structure on the power/ground plane
- **Step 3:** Analysis of noise suppression over the UWB band

Step 1: Design of Metamaterial-Inspired Resonator Structure

Initially, a square-shaped resonator is designed as the base structure, as shown in Figure 1. To improve stopband performance, a cross-dumbbell geometry is introduced, forming a Cross-Shaped Resonator (CSR) with enhanced metamaterial characteristics.

To further improve noise suppression, a Stub-Loaded Cross-Shaped Resonator (SLCSR**)** is derived from the CSR design. The narrow connecting strips introduce additional series inductance, which is further increased by introducing thin slots on the upper and lower sides of the resonator, as illustrated in Figure 2**.**

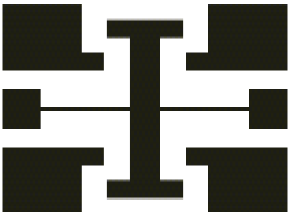

Fig 2. Stub loaded CSR EBG

By appropriately tuning the geometric dimensions, the effective inductance and capacitance of the metamaterial unit cell can be controlled, enabling flexible stopband positioning. The surrounding square patches contribute to the capacitance, while the interdigital pattern and shunt meander lines further enhance the loaded capacitance.

Step 2: Integration of Metamaterial Structure into PDN

The optimized SLCSR metamaterial structure is etched onto the power plane, and noise is injected through the ground plane to assess suppression performance. Comparative analysis shows that the PDN incorporating the SLCSR metasurface exhibits significantly improved noise attenuation compared to a uniform conductor plane.

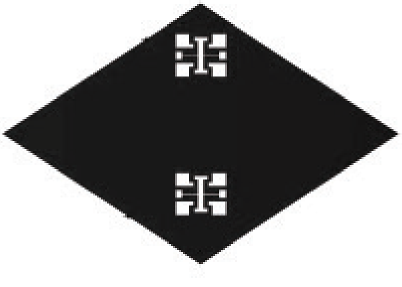

Fig 3. Perfect conductor plane with SLCSR EBG cell

Figure 3 illustrates the power plane embedded with the SLCSR metamaterial unit cell. A three-dimensional view of the structure is shown in Figure 4**,** where the microstrip line is designed for 50 Ω impedance matching using an FR4 substrate with εr = 4.6 and thickness of 1.6 mm. The model clearly demonstrates how injected noise is effectively suppressed by the metamaterial-based structure.

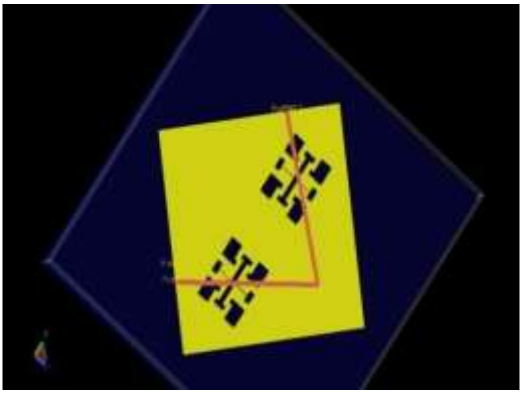

Fig 4. 3D view of the SLCSRR EBG

Step 3: Noise Suppression Enhancement over UWB Band
To achieve suppression levels exceeding –50 dB, three additional metamaterial-based enhancement techniques are employed**:** cascading**,** long-bridge interconnection, and long-bridge with vias.

A. Cascaded SLCSR Metamaterial Structure
Multiple SLCSR unit cells are cascaded to broaden the stopband and improve attenuation. Periodic resonator patterns are etched on the ground plane, while noise is injected through a single-ended trace on the power plane, as shown in Figure 5**.**

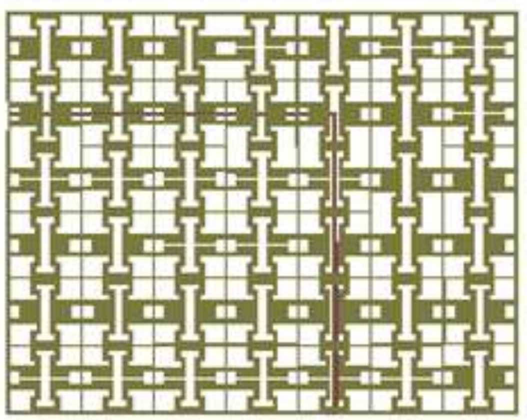

Fig 5.Cascaded SLCSR EBG

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B. Long-Bridge SLCSR Metamaterial Structure

Simulation results reveal that cascaded structures alone provide limited suppression at lower frequencies. To enhance low-frequency performance, long bridges are introduced between adjacent resonator rows, increasing series inductance and widening the stopband, as illustrated in Figure 6**.**

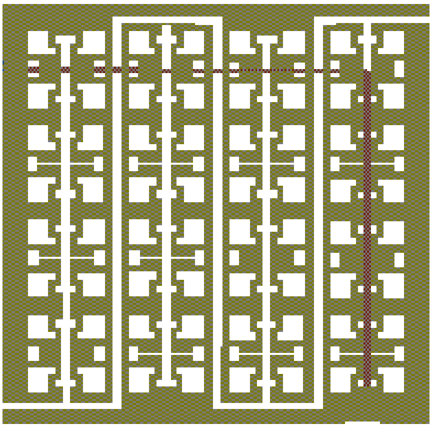

Fig 6. Long Bridge SLCSR EBG structure

C. Long-Bridge SLCSR Metamaterial Structure with Vias

PCB discontinuities such as vias and connectors often exacerbate SSN. To mitigate this effect**,** vias are incorporated into the metamaterial layer, enhancing low-frequency suppression and improving stopband continuity. The resulting configuration, shown in Figure 7, provides superior broadband attenuation.

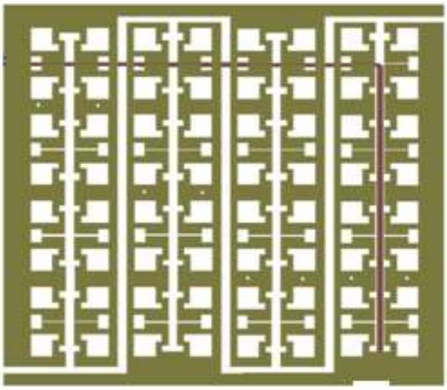

Fig 7. Long bridge SLCSR EBG with via

Fabrication and Experimental Validation

The test structures were fabricated on double-sided FR4 copper-clad laminates with a copper thickness of 35 μm. Standard photolithography was used to pattern the metamaterial resonators, stubs, and bridges. For the via-loaded configuration, precision drilling and copper plating were employed. All microstrip traces were designed for 50 Ω characteristic impedance. Measurements were carried out using a Advanced Design System (ADS), specifically a Keysight to accurately capture the S-parameters. SMA connectors were soldered onto each test board to ensure precise signal injection and measurement with minimal loss or mismatch. Prior to each measurement, the setup was calibrated using the Short-Open-Load-Through (SOLT) method to guarantee accurate and repeatable results. All frequency-domain measurements were conducted across a broad range from 0 GHz to 12 GHz to fully characterize the noise suppression performance within the ultra-wideband (UWB) spectrum.

3. Results and Discussion

The square-shaped cross-shaped resonator (CSR) metamaterial structure was initially designed and analyzed to establish its baseline noise suppression performance. The configuration consists of a central dumbbell-shaped resonator surrounded by four square patches, which effectively enhance the overall capacitance of the unit cell. To further improve the suppression characteristics, an interdigital metamaterial pattern was connected to shunt meander lines, thereby increasing the loaded capacitance and strengthening the high-impedance surface behavior. Both the basic CSR metamaterial structure and the stub-loaded CSR (SLCSR) metamaterial structure were simulated, and their comparative performance results are presented in Figure 8.

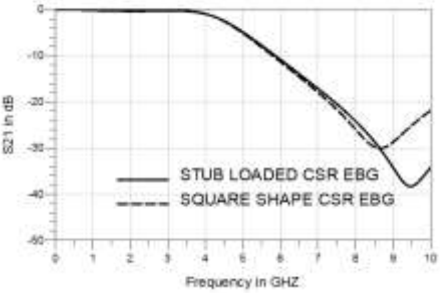

Fig 8 Comparison of Simulated S21 response of a square shape CSR EBG and Stub loaded CSR EBG

The simulation results reveal a clear performance trend: the basic CSR metamaterial structure achieves an attenuation level of approximately –30 dB, whereas the stub-loaded CSR (SLCSR) metamaterial structure provides a deeper attenuation of about –40 dB. This enhancement is attributed to the introduction of stubs and slots, which effectively increase the series inductance of the metamaterial unit cell, leading to an expanded stopband and stronger broadband noise suppression. These results confirm the effectiveness of stub loading in tailoring the resonant behavior of the proposed metamaterial structure.

To validate the practical applicability of the optimized design, the SLCSR metamaterial structure was etched onto an actual power plane and experimentally evaluated. Its performance was compared with that of a conventional power plane without any metamaterial pattern. The measured results, presented in Figure 9, clearly demonstrate a significant improvement in real-world noise suppression, validating the effectiveness of the proposed metamaterial-inspired design.

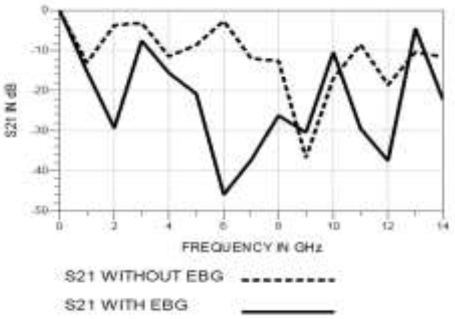

Fig 9 Comparison of Simulated S21 response of power plane

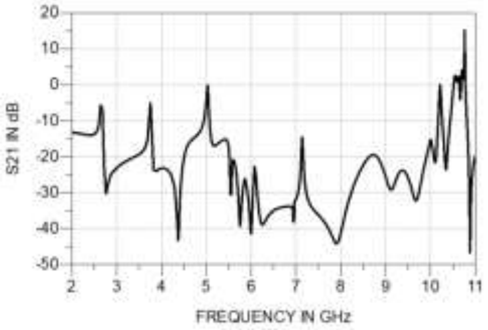

Fig 10. SimulatedS21 response of cascaded SLCSR EBG structure

From these results, it is observed that the power plane embedded with the SLCSR metamaterial structure achieves a maximum attenuation of approximately –46 dB, whereas the plain power plane exhibits only –36 dB attenuation. This clearly demonstrates that the incorporation of the SLCSR metamaterial-inspired resonator effectively suppresses simultaneous switching noise (SSN) across the ultra-wideband (UWB) frequency range.

To further extend the stopband bandwidth, a cascaded SLCSR metamaterial configuration was investigated. In this approach, multiple metamaterial unit cells are arranged in series to strengthen the periodic high-impedance surface (HIS) behavior, thereby enabling enhanced broadband noise suppression. The corresponding S21 response of the cascaded metamaterial structure is presented in Figure 10.

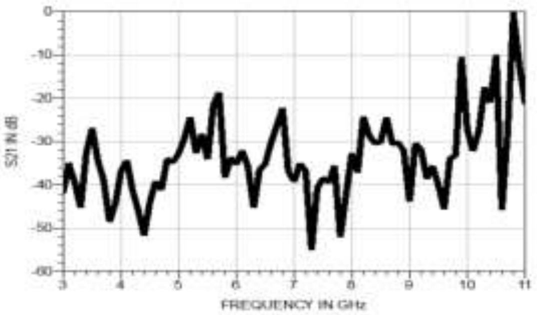

Fig11.Simulated S21 response of long bridge SLCSR EBG structure.

The cascaded configuration offers a moderate improvement in noise suppression, reaching an attenuation of about –45 dB and producing a flatter stopband compared to a single SLCSR unit cell. This demonstrates the cumulative effect of cascading metamaterial unit cells in widening the suppression bandwidth.

However, as observed in practical scenarios, the cascaded design still shows limited performance at lower frequencies, where the stopband remains relatively narrow. To overcome this limitation, a long-bridge SLCSR metamaterial structure was introduced. Connecting adjacent resonator patches with long bridges increases the effective series inductance, which shifts the stopband toward lower frequencies and broadens the overall suppression range. The corresponding simulated S21 response is presented in Figure 11.

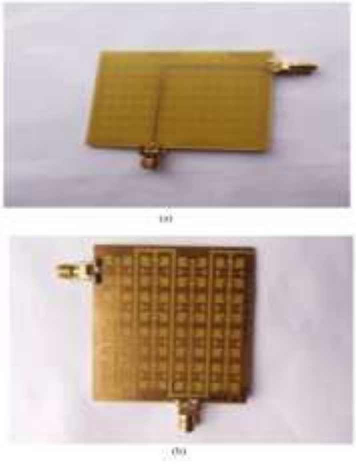

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Fig 12. Photograph of SLCSR EBG

The long-bridge SLCSR metamaterial structure achieves a maximum attenuation of approximately –52 dB, representing the best suppression performance among the planar metamaterial configurations investigated. This result indicates that enhanced inductive coupling within the metamaterial unit cells is an effective approach for mitigating simultaneous switching noise (SSN), particularly in the lower gigahertz frequency range.

Considering that practical printed circuit boards inherently contain vias, connectors, and cut-outs, a long-bridge SLCSR metamaterial structure incorporating vias was fabricated to evaluate the influence of such discontinuities under realistic conditions. The fabricated prototype and its corresponding top and bottom views are presented in Figure 12.

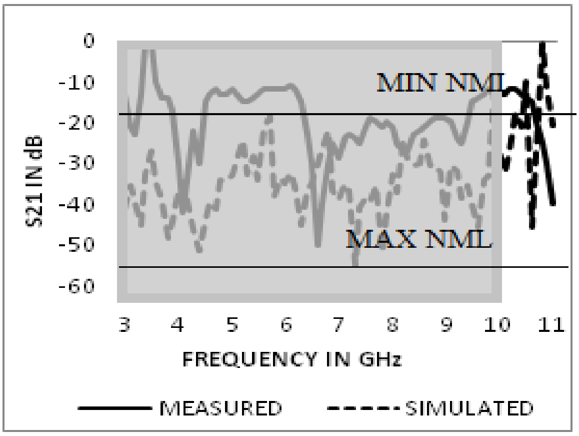

Fig13.Comparison of simulated and measured S21 response of long bridged SLCSR EBG with via.

The simulated and measured S21 responses of the final via-loaded long-bridge SLCSR metamaterial structure were compared to verify experimental validity, and the results are presented in Figure 13. The measured results closely match the simulated data, showing a maximum attenuation of around –55 dB and a minimum near –20 dB across the ultra-wideband frequency range. These findings demonstrate that the proposed metamaterial-inspired resonator structure effectively suppresses simultaneous switching noise (SSN), even in the presence of practical PCB discontinuities such as vias and connectors. The strong correlation between measurements and simulations further supports the reliability of both the design methodology and the electromagnetic simulation models used.

The proposed SLCSR metamaterial architectures demonstrate noise suppression exceeding –50 dB, offering a significant improvement over conventional approaches such as decoupling capacitors and split-plane designs. The combination of cascading, long-bridge interconnections, and via integration provides design flexibility, enabling adaptation to diverse PCB layouts and noise mitigation requirements.

Nonetheless, the increased size and structural complexity—especially in cascaded and long-bridge configurations—can lead to higher fabrication effort and require additional PCB space. Small variations observed near the stopband edges underscore the importance of more accurate modeling of parasitic effects, connector losses, and fabrication tolerances in future work.

The results achieved in SSN suppression demonstrate that SLCSR-based metamaterial structures have strong potential for integration into next-generation high-speed PCBs, including applications in wireless communication, high-speed computing, and RF front-end circuits. Future investigations could explore miniaturization techniques to reduce resonator footprints while preserving high suppression levels, as well as hybrid strategies that combine metamaterial designs with active noise cancellation or adaptive filtering to achieve broader and more robust suppression.

Table 1: Performance analysis of noise mitigation level

Method of mitigation	**Maximum suppression in dB**	**Minimum suppression in dB**
Cascading	-45	-15
Long bridge	-52	-11
Long bridge with via	-55	-20

Advanced fabrication methods, such as additive manufacturing and precision micro-drilling, may further facilitate the implementation of complex via and bridge geometries with enhanced repeatability. Moreover, comprehensive testing across multiple prototypes and alternative substrate materials would support the generalization of this PDN design methodology for a wide range of high-speed electronic systems. The performance summary of the proposed metamaterial-inspired noise mitigation structures is presented in Table 1.

4. Conclusion

A metamaterial-inspired approach for mitigating simultaneous switching noise (SSN) in high-speed planar circuits is presented, highlighting the performance of the stub-loaded cross-shaped resonator (SLCSR) metamaterial structure and its advanced configurations. Compared with conventional power/ground planes, even the basic CSR design provides significant noise attenuation. To enhance suppression, three advanced configurations—cascading, long bridge, and long bridge with vias—were analyzed. These structural modifications increase the effective series inductance and capacitance, broadening the stopband and achieving deeper attenuation. The long-bridge SLCSR metamaterial with vias demonstrated the highest suppression, particularly at lower frequencies, achieving a maximum attenuation of approximately –55 dB across the ultra-wideband (0–12 GHz) spectrum. The experimental measurements were in close agreement with the simulations, validating both the reliability and practical feasibility of the design. These metamaterial structures provide effective wideband noise suppression for high-speed digital, RF, and wireless systems, while remaining adaptable to various substrates and PCB layouts.

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