Localized and Periodic Spiral-Shaped EBG Structures for the Simultaneous Switching Noise Mitigation

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Abstract—**In this paper, we study the techniques to obtain wider bandwidth using uniplanar EBG power plane for simultaneous switching noise (SSN) mitigation and propose localized or periodic spiral-shaped EBG structures which can effectively suppress the SSN when the power plane drives high-speed ICs. The proposed structures have wider stopband bandwidth than conventional EBG structures, from 0.15 GHz to more than 6 GHz.**

I. Introduction

Simultaneous switching noise (SSN) is one of the most important issues in designing modern high-speed digital circuits with high clock frequencies and low supply voltage levels. When the driver ICs switch rapidly on a package or multilayer PCB, the SSN or ground bounce noise (GBN) is caused by rapid time-varying currents. The SSN on the power/ground planes causes electromagnetic interference (EMI) issue by the resonance modes between the power and ground planes. Also it affects signals passing through peripheral via holes and brings significant signal integrity (SI) problems. Therefore it is essential to eliminate the SSN.

Several techniques to suppress the SSN have been proposed for several years. The typical method is to use the decoupling capacitors located between the power plane and ground plane. But the decoupling capacitor is not effective in frequency region higher than 600 MHz because of the self-resonance effect associated with effective series inductance of the capacitor [1],[2]. Accordingly, to suppress the SSN above 1 GHz, the power/ground plane design using electromagnetic bandgap (EBG) or photonic bandgap (PBG) has been extensively studied recently. The EBG prevents electromagnetic waves from propagating in a specified frequency range, which results in a stopband. The representative EBG structure is a mushroom-type EBG structure which consists of metal pads connecting to the ground plane through via holes. The mushroom-type EBG structure is inserted between the power plane and the ground plane, which makes the fabrication more expensive [3],[4]. Then the power planes that utilize new uniplanar EBG structures were reported for switching noise mitigation as in [5]-[7]. These new structures are composed of a power plane patterned in a periodic uniplanar EBG and solid ground plane, without via holes. This feature makes the structures very attractive in terms of manufacture and cost.

But the uniplanar EBG structures are periodically and uniformly distributed on a whole power plane, which results in many surfaces of discontinuity. The surfaces of discontinuity affect signal return currents to cause SI problem when the signal traces pass above the power plane. In addition, the performance of these EBG structures depends on the port location, so it is not easy to use them widely in a realistic situation [8]. We do not need to use the periodic EBG structures which may lead to SI degradation sometimes due to the surfaces of discontinuity, if the high speed digital system requires few driver ICs.

In this paper, we introduce a novel uniplanar EBG structure, which locates itself only around the via holes generating the SSN, and extend its concept to a periodic structure. And we show that it has a wider stopband than conventional EBG structures, although the EBG unit cell size is reduced. To verify its performance, the proposed structure is numerically simulated by using commercial software of Microwave Studio [9] and is implemented on a FR4 PCB substrate. The measured results of the proposed structure are presented and compared with the conventional EBG structures. The results show that the proposed structure, in a localized form or a periodic form, has much better performance than the conventional EBG structures.

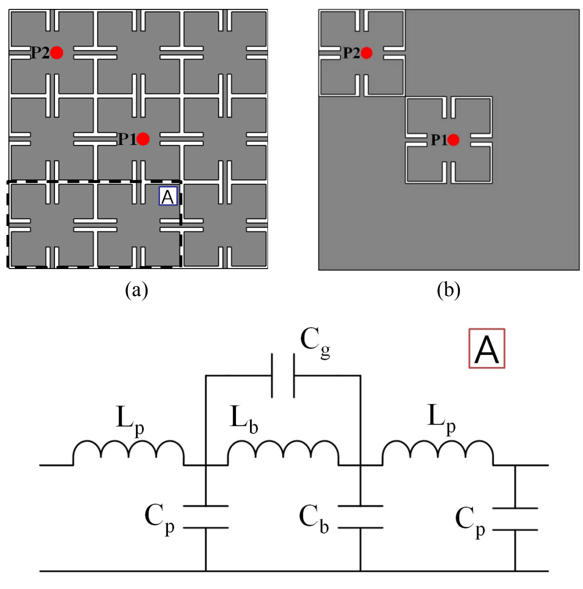


Fig. 1 Conventional EBG structure (a) Periodic EBG structure [5] (b) Localized EBG structure (c) Equivalent circuit model for the two connecting unit cells in Fig. 1(a) [5]

TABLE I
EFFECTS OF THE BRIDGE INDUCTANCE VARIATION

Inductance L_b	Start frequency	Stop frequency
2.6 nH	1.16 GHz	5.25 GHz
26 nH	0.43 GHz	4.93 GHz
260 nH	0.14 GHz	4.92 GHz

TABLE II
EFFECTS OF THE GAP-COUPLING CAPACITANCE VARIATION

Capacitance C_g	Start frequency	Stop frequency
1.5 pF	1.17 GHz	4.81 GHz
1 pF	1.16 GHz	5.24 GHz
0.5 pF	1.16 GHz	5.85 GHz

II. A SPIRAL-SHAPED EBG STRUCTURE

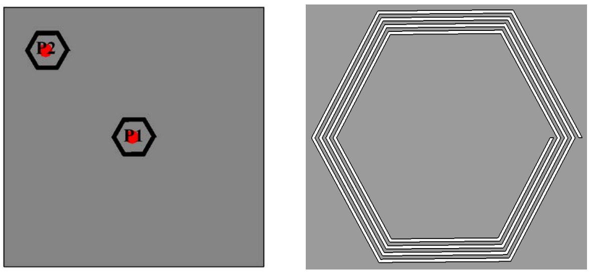
A. Design Concept

Fig. 1 shows a conventional EBG structure on the power plane. A unit cell of the conventional EBG structures is typically a rectangular or hexagonal shape, and the size is 30 mm×30 mm in most cases. The EBG unit cells are periodically and uniformly distributed on a whole power plane as shown in Fig. 1(a). This EBG structure consists of square metal pads and bridges connecting them. Fig. 1(c) shows an equivalent circuit model for two neighboring unit cells in Fig. 1(a). It consists of the two parts. First, equivalent inductance L_P (0.475 nH) and capacitance C_P (39 pF) describe the propagation characteristic between the square metal pad on the power plane and the solid ground plane. Second, bridge inductance L_b (2.676 nH), bridge capacitance C_b (1.4 pF), and gap coupling capacitance C_g (0.996 pF) describe the bridging effect [5]. As shown in the equivalent circuit, the noise cannot propagate due to parallel LC resonance.

In order to obtain more improved stopband characteristic of the EBG structure, we look into a trend with the variation of the L_b and C_g, when L_p and C_p are not changed. Table I and Table II summarize the effects of the L_b and C_g variation. These results are obtained from equivalent circuit simulation using ADS. As a result of this study, to get wider bandwidth, the bridge inductance should be larger and the gap-coupling capacitance should be smaller.

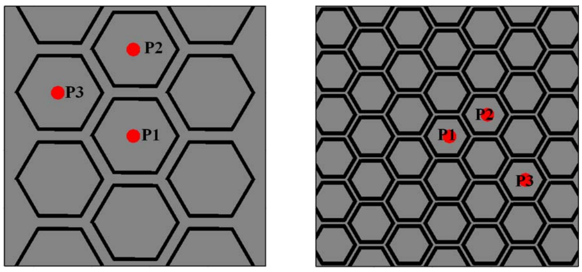
B. Proposed EBG Structure

To achieve better SSN suppression, we proposed the novel spiral-shaped EBG structure which locates itself only around via holes generating the SSN, when the power plane supplies power to the driver ICs [10]. In this paper, we extend the localized spiral-shaped EBG structure to a periodic spiral-shaped EBG structure. In the localized EBG structure, the power plane is kept a solid plane except around the ports as shown in the Fig. 2(a). The substrate conditions are as follows. The relative dielectric constant and thickness of the substrate are 4.1 and 0.4 mm, respectively. Total substrate size is 90 mm×90 mm. The proposed EBG unit cell is presented in Fig. 2(b). The structure has an inner hexagon with a diagonal line of 12 mm and three turns of the metal line that connects the power planes. The width and gap of the metal line around the hexagonal pad are 0.2 mm, respectively. The design parameters are obtained through an optimal process for achieving wider stopband bandwidth. The proposed unit cell has a extended thin line around the hexagonal pad to increase its bridge inductance for efficient noise suppression at low frequency regions and to decrease its gap-coupling capacitance for efficient noise suppression at high frequency regions.



(a) (b)

Fig. 2 Proposed spiral-shaped EBG Structure (a) The localized EBG structure (b) The proposed unit cell



(a) (b)

Fig. 3 Proposed periodic spiral-shaped EBG Structure (a) 30 mm×30 mm unit cell (b) 15 mm×15 mm unit cell

Although the proposed spiral-shaped structure is designed for a localized EBG, if preventing the noise generation outside the localized EBG cell is more important than the SI problem of the signal trace, the proposed EBG unit cell can be extended periodically. In Fig. 3, the power planes of the proposed periodic spiral-shaped EBG structure are shown. The substrate conditions are same as before. The proposed EBG structures are periodically and uniformly distributed on a whole power plane at an interval of 30 mm and 15 mm, respectively.

III. MEASUREMENT AND SIGNAL INTEGRITY

A. Wide Band SSN Suppression

To verify the SSN suppression characteristics of the proposed EBG structure, it was numerically simulated and measured [10]. To compare their performances when the conventional EBG unit cells are used locally, we simulated and measured the conventional periodic EBG structure of Fig. 1(a) and localized EBG structure of Fig. 1(b) while maintaining the same conventional unit cell size, and decreasing the cell size by half. The substrate conditions are same as them of the proposed EBG structure. And the ports on the PCB are located at the same positions as in the conventional EBG structure of Fig. 1 in each case.

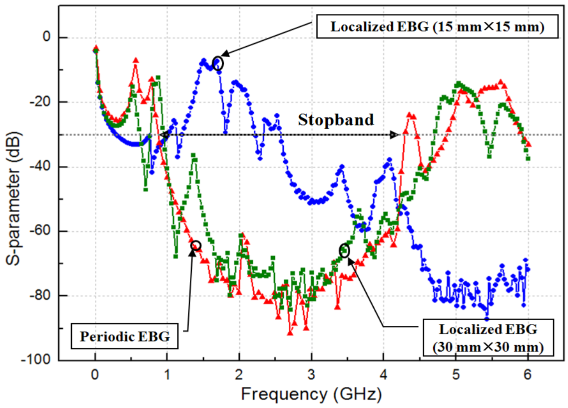


Fig. 4 Measured results of periodic and localized conventional EBG structures

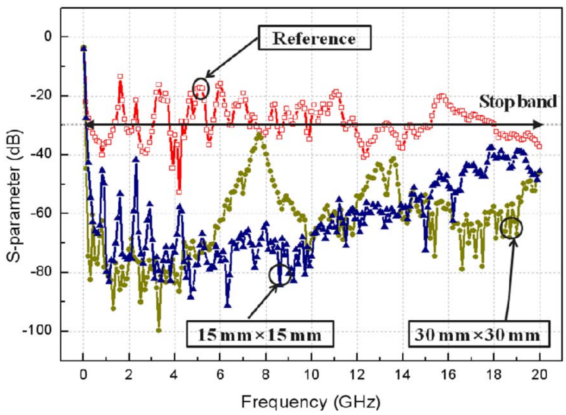


Fig. 5 The measured results of the proposed localized EBG structures

Fig. 4 shows the measured results of the conventional EBG structure in Fig. 1. They show that the localized EBG structure has very similar performance to the conventional periodic structure, if the unit cell size is maintained to be same (30 mm×30 mm). But as shown in Fig. 4, if the unit cell size reduces to 15 mm×15 mm, the performance of the localized EBG structure can be greatly deteriorated and cannot suppress the SSN well.

In Fig. 5, the SSN suppression characteristics of the proposed localized structure are presented and compared with a reference plane which is a solid plane without discontinuity. As shown in the figure, based on the -30 dB suppression level, the proposed localized structure with 30 mm×30 mm unit cell has a wide stopband from 0.05 GHz to more than 20 GHz. And when the unit cell size is 15 mm×15 mm, the stopband of the proposed EBG structure is from 0.15 GHz to more than 20 GHz. Fig. 6 shows the measured results of the proposed periodic EBG structure. Fig. 6(a) shows a stopband of 0.1 GHz up to 7 GHz. And Fig. 6(b) shows a wide stopband of maximum 12 GHz. The periodic structure also has a good SSN suppression characteristic like the localized spiral-shaped EBG structure.

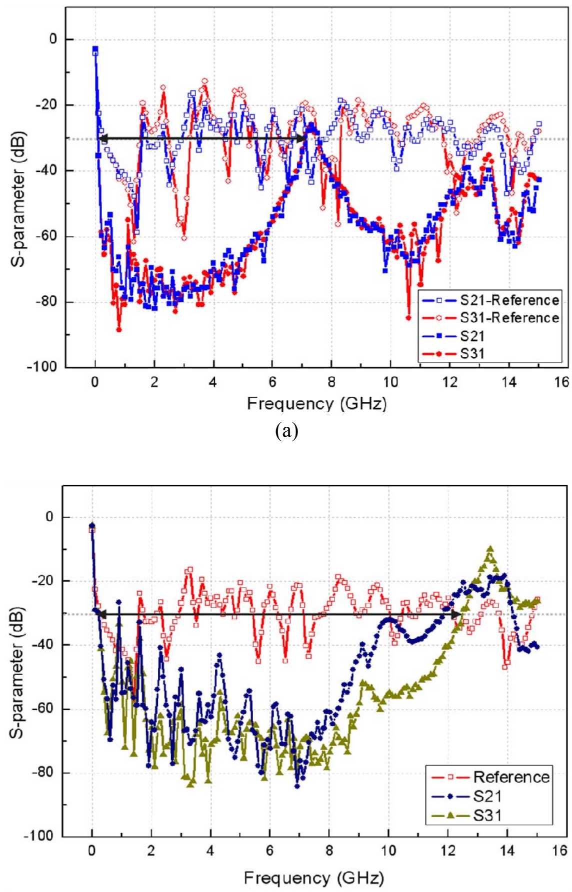


Fig. 6 The measured results of the proposed periodic EBG structure (a) 30 mm×30 mm unit cell (b) 15 mm×15 mm unit cell

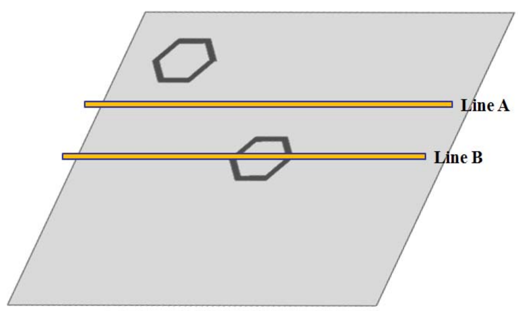
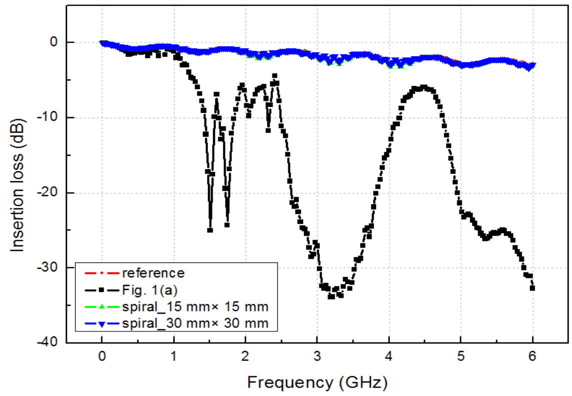


Fig. 7 Test PCB for signal integrity measurement

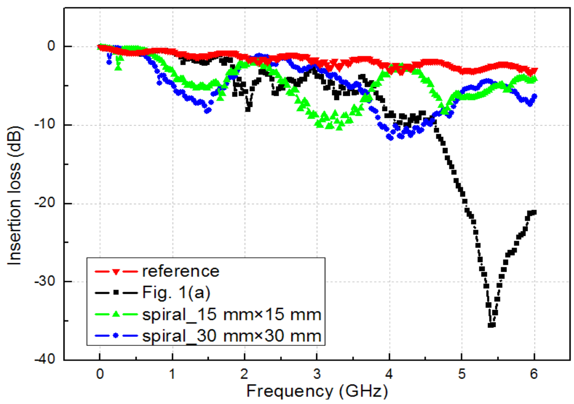
The suppression characteristics of the proposed EBG unit cell are better than them of the previous reported conventional EBG cells when it is locally or periodically used with the same cell size as well as reduced cell size.

B. *Signal Integrity*

Since the surfaces of discontinuity of the power plane utilizing the uniplanar periodic EBG structures are periodically and uniformly distributed, they affect the signal return currents following the reference plane, when the signal traces pass above the power plane. Therefore, it may cause SI problems. To consider the SI problems of the proposed localized EBG structure, we use the test PCB with the signal trace on a top layer and the EBG power plane on a bottom layer as shown in Fig. 7. In this experiment, a solid power plane as a reference, conventional EBG in Fig. 1(a), and localized spiral-shaped EBG are applied to the power plane. The line A and line B in Fig. 7 mean the traces at different positions. When the signal flows along the trace, we measure the insertion loss (S_{21}) of the trace, in order to compare the losses due to the surfaces of discontinuity on the power plane.



(a)



(b)

Fig. 8 The measured results of the test PCB (a) Line A (b) Line B

The measured results are shown in Fig. 8. According to the results, the proposed localized EBG structure has less loss than the conventional EBG structure. The ripples are observed due to impedance mismatch. When the conventional EBG is applied to the power plane, the line A and line B have large loss in the mass. But in case of the proposed EBG, the line A has much lower loss and the line B has slightly lower loss than the conventional EBG. This is because the proposed EBG has fewer surface discontinuities than the conventional EBG.

When we design the high-speed digital system using the proposed localized EBG power plane, by placing the signal traces on the area outside the localized EBG cell, we can avoid the SI problem and suppress the SSN effectively over the whole frequency bands.

IV. CONCLUSIONS

In this paper, to obtain wider bandwidth using uniplanar EBG power plane for the SSN mitigation, we studied the new technique to increase the bridge inductance and to decrease the gap-coupling capacitance between the EBG unit cells. And we proposed the spiral-shaped EBG cell to effectively suppress the SSN around the noise-generating ports. We also distributed the proposed cells periodically to suppress the SSN of the whole power plane. The proposed EBG structures are expected to be effectively used in the high-speed digital system.

ACKNOWLEDGMENT

This research was supported by the MKE(Ministry of Knowledge Economy), Korea, under the ITRC(Information Technology Research Center) support program supervised by the IITA(Institute of Information Technology Advancement). (IITA-2008-(C1090-0801-0034))

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