Bandwidth Enhancement for SSN Suppression Using a Spiral-Shaped Power Island and a Modified EBG Structure for a λ/4 Open Stub

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This paper proposes a spiral-shaped power island structure that can effectively suppress simultaneous switching noise (SSN) when the power plane drives high-speed integrated circuits in a small area. In addition, a new technique is presented which greatly improves the resonance peaks in a stopband by utilizing λ/4 open stubs on a conventional periodic electromagnetic bandgap (EBG) power plane. Both proposed structures are simulated numerically and experimentally verified using commercially available 3D electromagnetic field simulation software. The results demonstrate that they achieve better SSN suppression performance than conventional periodic EBG structures.

Keywords: Simultaneous switching noise (SSN), electromagnetic bandgap (EBG), spiral-shaped power island, resonance peak suppression.

Manuscript received May 6, 2008; revised Jan. 2, 2009; accepted Jan. 24, 2009.

This research was supported by the MKE (Ministry of Knowledge Economy), Rep. of Korea, under the ITRC (Information Technology Research Center) support program supervised by the IITA (Institute of Information Technology Advancement) (IITA-2009-(C1090-0902-0034)).

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I. Introduction

Today, as the demand for digital systems with higher data speeds and wider bandwidths grows, a fast edge rate for clock frequencies becomes important. Therefore, simultaneous switching noise (SSN) and ground bounce noise (GBN) on a package or multilayer PCB are also an important issue in high-speed digital systems. SSN is caused by rapid time-varying currents, and it affects signals that pass through the peripheral via holes and brings about electromagnetic interference. A typical method of SSN mitigation is to use decoupling capacitors between the power plane and the ground plane. However, the use of a decoupling capacitor is not an effective technique in frequency regions higher than several hundred MHz due to the parasitic inductance in this region [1], [2].

As a viable approach in the GHz region, a power/ground plane design using electromagnetic bandgap (EBG) or photonic bandgap (PBG) structures has been extensively studied recently. An EBG structure has a high impedance surface that has a perfect magnetic conductor at a specific frequency band. It is capable of blocking surface currents [3].

The typical EBG structure is a mushroom-type EBG that consists of metal pads connected to the ground plane through via holes. The mushroom-type EBG structure is inserted between the power plane and the ground plane. The extra layer of metal required for an array of patches and the extra array of via holes increase the manufacturing cost relative to patterning only the power or ground planes with a periodic pattern [4], [5]. For this reason, it is desirable to use mushroom-type structures in some higher current applications, where the cost of an extra layer of metal is justified to obtain lower levels of self and mutual impedance in the power distribution network.

EBG power planes that keep the ground plane solid have been proposed [6]-[10]. These EBG power planes are very attractive in terms of manufacturing and cost because they do not require multilayer structures. However, the EBG patterns should be distributed periodically and uniformly over the entire power plane. As a result, an EBG power plane has many surfaces of discontinuity. The surfaces of discontinuity perturb the returning signal currents following a reference plane, which can cause signal integrity (SI) problems. Moreover, the performance of these EBG power planes is highly dependent on the signal port location, complicating their wider use in actual situations. If a digital system requires few driver integrated circuits (ICs), use of a periodic EBG power plane that may lead to SI degradation due to the surfaces of discontinuity is often unnecessary. Therefore, in section II, a spiral-shaped power island is proposed which is located only around the via holes generating the SSN when the power plane supplies power to the driver ICs. To verify the performance, a three-dimensional electromagnetic field simulation of the proposed structure is conducted using the commercial software Microwave Studio [11]. Measured data is also provided.

Another problem with conventional EBG structures involves the peaks in the stopband region of the simulated and measured S-parameter results. For more stable SSN mitigation, they should be suppressed. Therefore, in section III, this study introduces a new technique which selectively suppresses the peaks at specific frequencies through the introduction of $\lambda/4$ open stubs into the EBG structures. The proposed structures are numerically simulated, and their results are compared to those of conventional EBG structures. The measured results are also given and compared with the simulation results. Finally, both proposed structures are validated and are presented numerically and experimentally.

II. Spiral-Shaped Power Island

1. Proposed Power Island

Figures 1(b) and (d) show power planes which use conventional EBG structures for SSN suppression [6], [10]. The conventional EBG structures have rectangular or hexagonal unit cells, and their size is 30 mm×30 mm in most cases. The unit cells are shown in Figs. 1(a) and (c). Each cell consists of a square metal pad and bridge lines that connect the unit cells. These structures have an inherent stopband where noise cannot propagate due to parallel inductance-capacitance resonance.

Figure 2 shows an equivalent circuit model of an EBG unit cell on a power plane [12]. The dotted box in the figure is a parallel LC resonant circuit which creates a stopband. In the resonant circuit, the inductance, L, is derived from the bridge line between the unit cells. The capacitance is mainly derived from the gap coupling of the square metal pads. Considering the LC resonant circuit in the dotted box, it is possible to evaluate the effects of the L and C values on its stopband bandwidth. While maintaining the same resonant frequency, if C is decreased, or L is increased, the stopband performance improves as shown in Fig. 3. Figure 3 is plotted to compare the relative effects of L and C based on the normalized frequency ($\omega^2 LC$=1). Therefore, to achieve a wider noise stopband, the bridge line inductance should be larger, and the gap-coupling capacitance should be smaller.

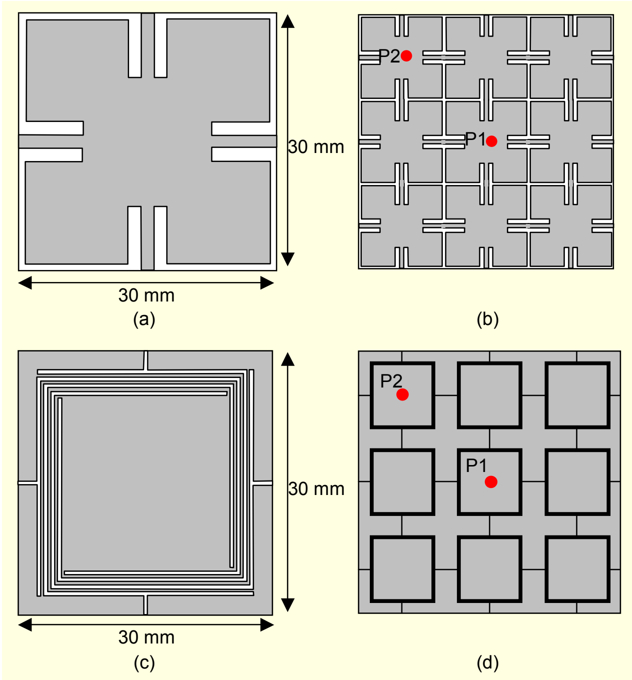

Fig. 1. Conventional EBG structures: (a) a basic rectangular cell, (b) a power plane using basic rectangular cells periodically, (c) a hybrid cell, and (d) a power plane using hybrid cells periodically.

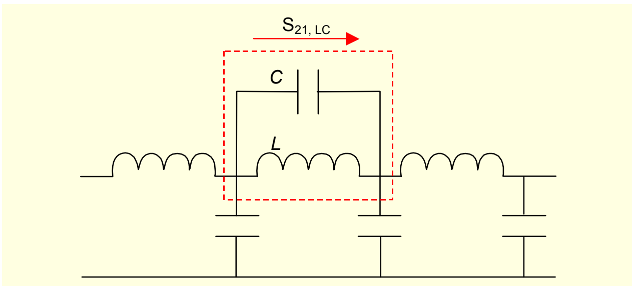

Fig. 2. Equivalent circuit model of an EBG unit cell.

To reduce the effect of the surfaces of discontinuity, it is

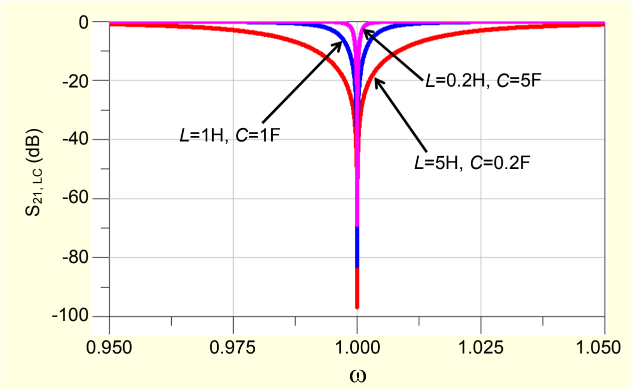

Fig. 3. Stopband variation with L and C values at a fixed resonant frequency.

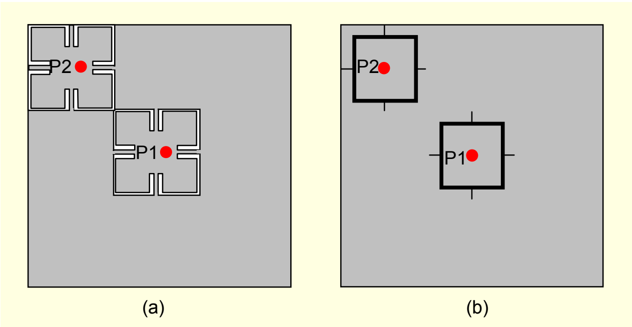

Fig. 4. Power planes locally using (a) basic rectangular cells and (b) hybrid cells.

possible to locally utilize conventional EBG unit cells only around the signal ports (P1 and P2) generating the SSN in the form of a power island as shown in Fig. 4 [13], [14]. The relative dielectric constant and thickness of the substrate are 4.1 and 0.4 mm, respectively. The entire substrate is 90 mm×90 mm. Figure 5 gives the measured results of the power islands shown in Fig. 4. All S-parameter measurements in this study are performed with a system reference impedance of 50 Ω. The power island is very similar in terms of performance to a conventional periodic EBG structure if the unit cell size is held constant (30 mm×30 mm). As shown in Fig. 5, if the unit cell size is reduced to 15 mm×15 mm, the power island cannot suppress the SSN well, which leads to a deterioration of the performance.

Therefore, to achieve good SSN suppression with small cells, a spiral-shaped power island is proposed. The structure has a hexagonal spiral-shaped pad and extends a thin line around the pad to increase its inductance and to decrease its gap-coupling capacitance for efficient noise suppression. The proposed spiral-shaped power island and a power plane utilizing the proposed power islands are shown in Fig. 6.

The width of the extended thin line is denoted by w and the gap between the lines is indicated by g as shown in Fig. 6(a). The

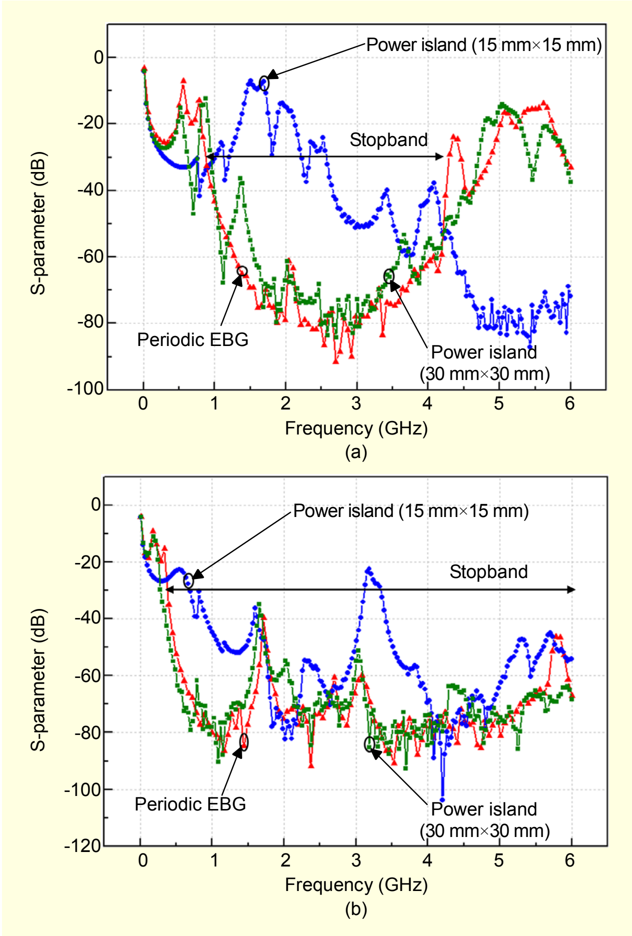

Fig. 5. Measured S_{21} results of the periodic EBG power planes and power islands with (a) basic rectangular cells and (b) hybrid cells.

number of turns of the line is denoted by T. The pad size can change in proportion to the size of the power island. First, the effects of w and g are investigated, with w and g both being 0.2 mm, 0.5 mm, and 1.0 mm, in succession. Figure 7(a) shows the simulated results of the spiral-shaped power island with various w and g values when T is 1 and the island size is 15 mm×15 mm. The low-frequency SSN suppression improves when w and g decrease. This implies that increases in the bridge line inductance lead to greater suppression of the SSN in a low-frequency region. Therefore, w and g should be small. Hence, w and g were both set to 0.2 mm, and T was changed from 1 to 3. Figure 7(b) shows the simulated results for T when the island size is 15 mm×15 mm and w and g are both 0.2 mm. As shown in the figure, for generally stable SSN suppression, T should be greater than 2. Therefore, T was set to 3, and w and g were both set to 0.2 mm with a unit cell size of 15 mm×15 mm.

As shown in Fig. 6(a), the proposed power island has an inner hexagon with a diagonal line of 12 mm and three turns of the metal line connecting the inner power pad to the outer

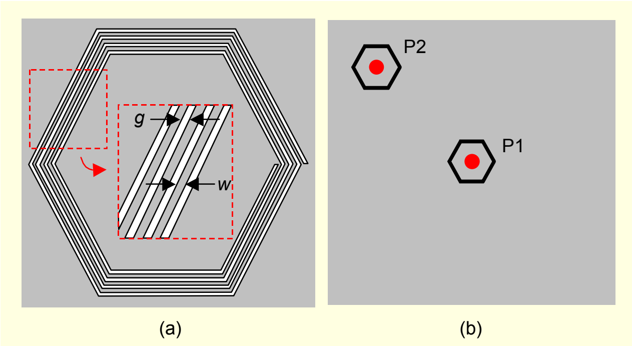

Fig. 6. (a) Proposed spiral-shaped power island structure and (b) a power plane using the proposed structures locally.

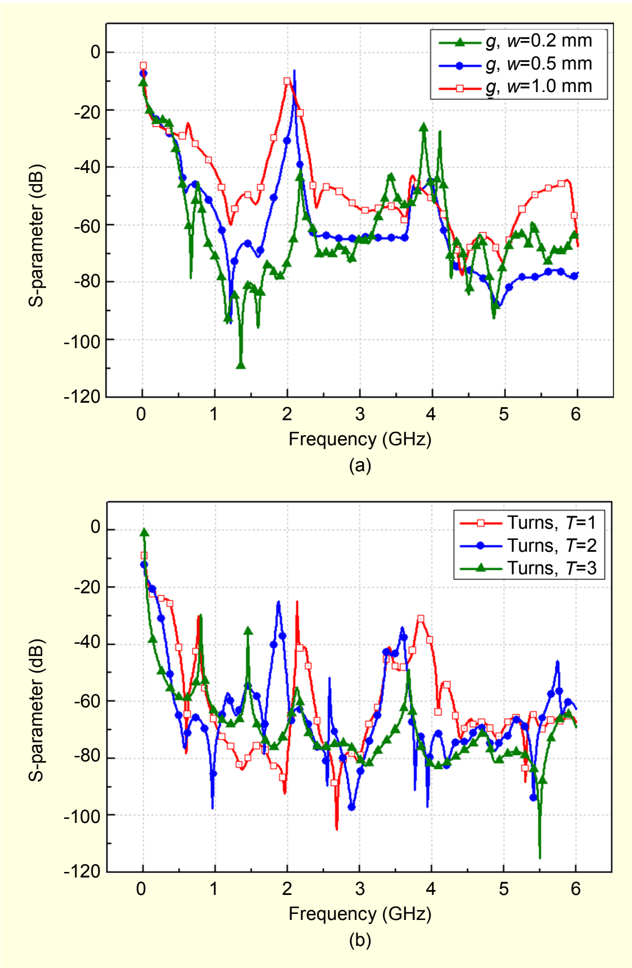

Fig. 7. Simulation results of the spiral-shaped power island structures with (a) w and g values and (b) T values.

power plane. The width and gap of the metal line around the hexagonal pad are 0.2 mm. The proposed spiral-shaped power island structure has considerable bridge line inductance and low gap-coupling capacitance. Therefore, it has a wider stopband than conventional EBG structures, although the unit cell size is reduced.

2. S-Parameters of the Spiral-Shaped Power Island

To validate the SSN suppression characteristics of the proposed spiral-shaped power island, a PCB was fabricated with the proposed power plane and a solid ground plane. The substrate parameters are identical to those shown in Fig. 4. The signal ports on the PCB are located at the same positions as in Figs. 1 and 4.

The SSN suppression characteristics of the proposed structure are shown in Fig. 8(a). The measured results are similar to the simulated results. Based on a suppression level of -30 dB, the proposed power plane with a spiral-shaped power island of 30 mm×30 mm has a wide stopband ranging from 0.05 GHz to more than 6 GHz. When the size was reduced to 15 mm×15 mm, the stopband ranged from 0.15 GHz to more than 6 GHz. In both cases, the noise suppression is very stable

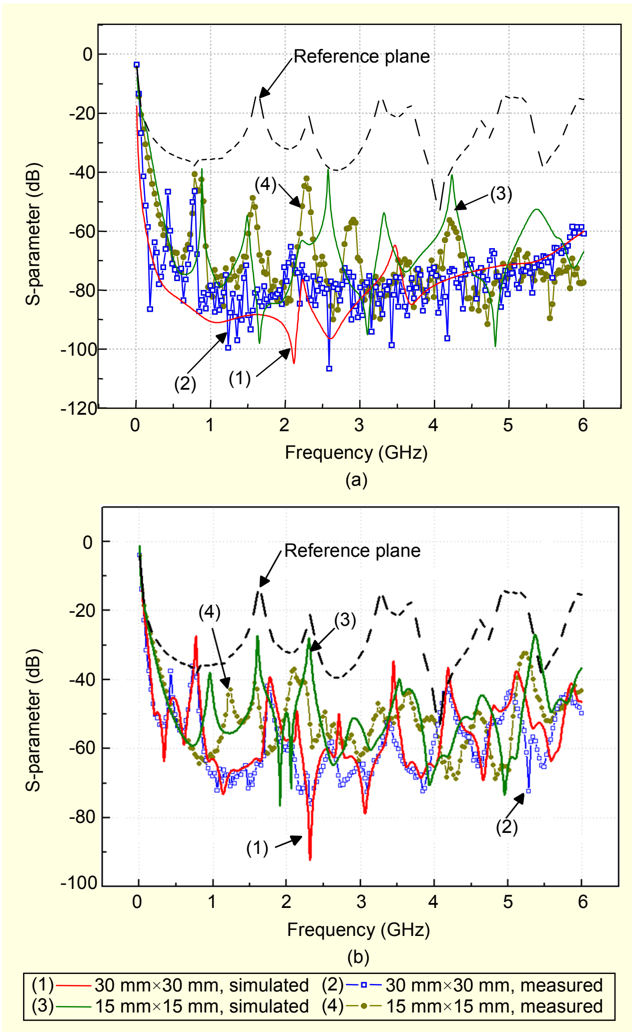

Fig. 8. Simulated and measured results of the proposed power plane with (a) spiral-shaped power island structures applied to both signal ports (P1 and P2) and (b) applied to only one signal port (P1 or P2).

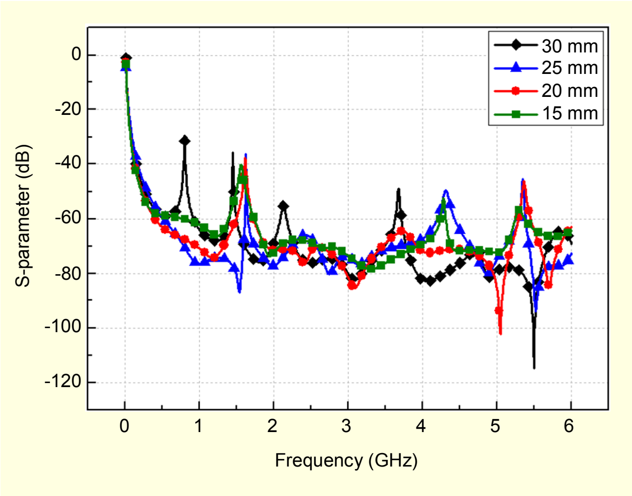

Fig. 9. Simulated results of the proposed power plane with various distances between the spiral-shaped power island structures.

because it appears below -40 dB in the stopband. The proposed power island has suppression characteristics that are superior to those of previous power planes with conventional EBG unit cells when a spiral-shaped power island is used with the same cell size or a reduced cell size.

The characteristics of the proposed spiral-shaped power island were then checked when it was applied to only one signal port in two measurement ports (P1 and P2 in the previous figures) on the power plane. Figure 8(b) shows the simulated and measured results. An island size of 30 mm× 30 mm resulted in a wide stopband ranging from 0.1 GHz to more than 6 GHz. This result is very similar to the case in which the proposed spiral-shaped power island was applied to both measurement ports (P1 and P2) on the power plane. When the size was 15 mm×15 mm, the stopband ranged from 0.2 GHz to 5.4 GHz based on a suppression level of -30 dB.

The proposed power plane was also simulated with a distance between the spiral-shaped power islands. The distance was varied between 15 mm and 30 mm at intervals of 5 mm. The simulated results are shown in Fig. 9. The suppression level of the power plane with the spiral-shaped power island with a distance of 15 mm is similar to that of the power plane with the spiral-shaped power islands with a distance of 30 mm. These results demonstrate that the SSN suppression level is not directly proportional to the distance between the spiral-shaped power islands.

According to these results, the proposed power island structure provides the possibility of efficiently confining the SSN to noisy ports when the driver ICs are densely integrated in a small area. Moreover, it is possible to use the proposed power island effectively in actual situations.

3. Signal Integrity

A periodic EBG structure on a power plane has many surfaces of discontinuity. When a signal trace passes above a power plane utilizing a uniplanar periodic EBG structure, many surfaces of discontinuity affect the returning signal currents following the reference plane. This may cause an SI problem. To verify that the SI characteristics of the proposed spiral-shaped power island are superior to those of conventional periodic EBG power planes, the structure shown in Fig. 10 was fabricated and tested. The test structure consists of a signal trace on the top layer and a power plane with conventional EBG unit cells or power islands as the bottom layer. To compare the proposed power island with the conventional EBG power planes, the transmission characteristics (S_{21}) of the trace were measured when the signal passed above the power plane.

Measured results are shown in Fig. 11. Figure 11(a) shows the measured S_{21} data of the signal traces above the conventional EBG power planes shown in Fig. 1(b) and (d). This measured data is compared with that of the reference power plane (solid power plane). The conventional EBG power planes show greater insertion loss over the entire frequency range. The power plane shown in Fig. 1(d) incurs greater insertion loss than that shown in Fig. 1(b) because the former has more surfaces of discontinuity than the latter. These results demonstrate that as a greater amount of signal trace crosses the discontinuity surfaces, degradation of the transmission performance increases.

Figure 11(b) shows the measured S_{21} data of the signal trace above the power plane with the proposed spiral-shaped power island. These measurements are also compared with that of the reference power plane. The proposed power plane incurs an insertion loss that exceeds -10 dB. This is a better result than those of conventional EBG power planes, as the trace encounters fewer discontinuity surfaces. Ripples in the transmission characteristics are observed due to the mismatch between the trace line impedance and measurement reference impedance of 50 Ω. If the signal trace is placed away from the

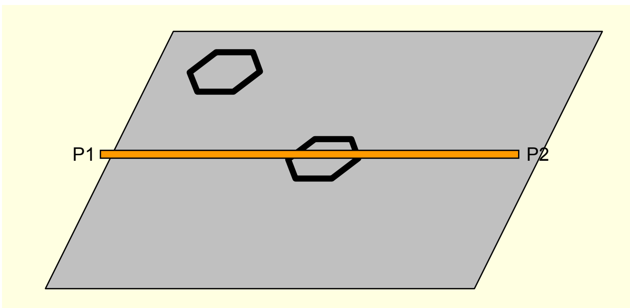

Fig. 10. Test structure for comparison of the signal integrity.

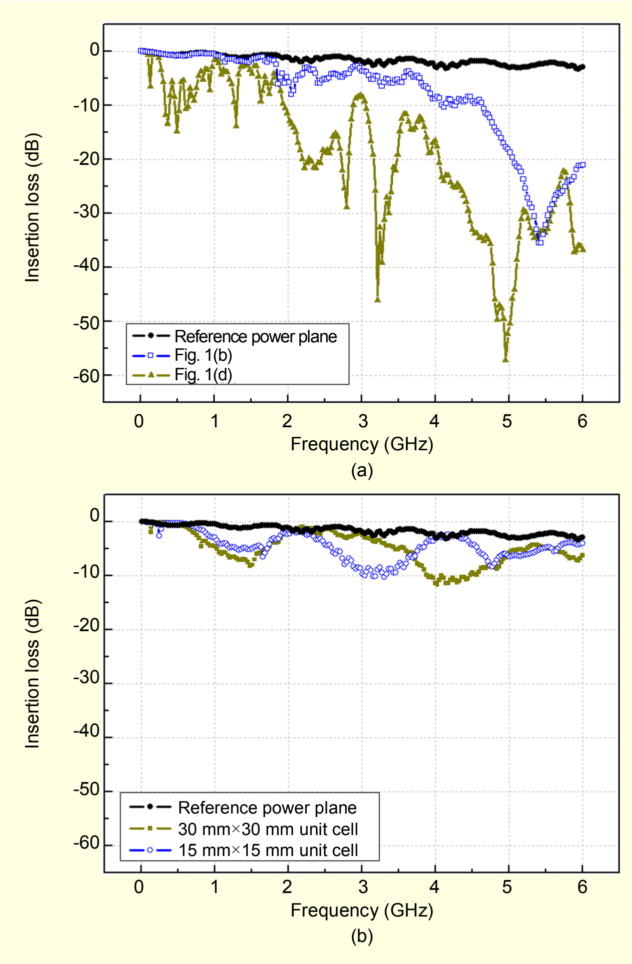

Fig. 11. Measured results of the signal traces above (a) conventional periodic EBG power planes and (b) the proposed power plane with spiral-shaped power islands.

surfaces of discontinuity, the proposed power plane has transmission characteristics that are nearly identical to those of the reference power plane.

Therefore, when a high-speed digital system is designed using the proposed spiral-shaped power island, by placing the signal traces on an area outside the power island, the SI problem is avoided and SSN is suppressed effectively over the entire frequency band.

III. Modified EBG Structure with Open Stubs for Resonance Peak Suppression

Some conventional EBG structures have transmission peaks in the stopband region. These peaks may cause unpredictable resonance that degrades the signal integrity and radiates interfering signals outward. For more stable SSN suppression, a new technique is proposed which selectively eliminates the peak at a specific frequency by introducing a λ/4 open stub into

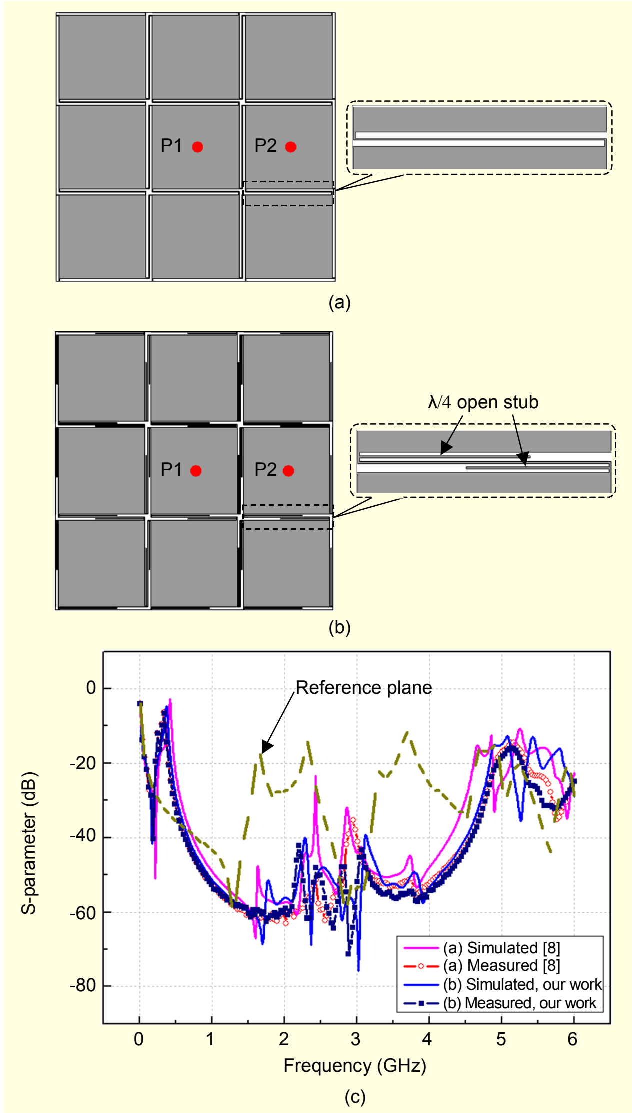

Fig. 12. Conventional and modified L-bridge EBG power planes with (a) conventional EBG structures [8] and (b) modified L-bridge EBG structures with λ/4 open stubs, and (c) their simulated and measured results.

the EBG structure. The added λ/4 open stub causes an electrical short at the specific frequency and suppresses the noise signal.

To verify the open stub effect, λ/4 open stubs were applied to a conventional L-bridge EBG structure. Figures 12(a) and (b) show the conventional and modified L-bridge EBG structures, and the simulated and measured results are shown in Fig. 12(c). The simulated results demonstrate that the conventional L-bridge EBG structure has resonance peaks at approximately 2.4 GHz and 2.86 GHz [8]. Attempts were made to suppress 2.4 GHz and 2.86 GHz peaks using the modified L-bridge with two open stubs. The width of the L-bridge line and the open stub between the unit cells are both 0.2 mm. The length of the two open

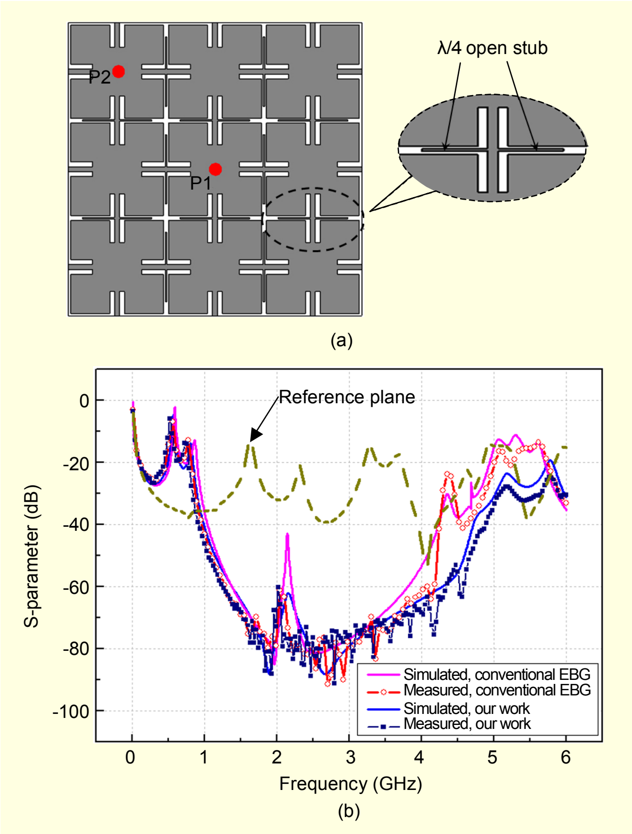

Fig. 13. (a) Modified EBG power plane with λ/4 open stubs and (b) its simulated and measured results.

stubs is 18.86 mm and 15.82 mm. These were calculated using ADS LineCalc software. The two open stubs were attached to both sides of the bridge line connecting the EBG cells as shown in Fig. 12(b). The relative dielectric constant and thickness of the substrate are 4.1 and 0.4 mm, respectively. The overall substrate size is 90 mm×90 mm and the EBG unit cell size is 30 mm×30 mm.

According to the simulated results shown in Fig. 12(c), the peaks are effectively suppressed from -23 dB to -52 dB at 2.4 GHz and from -31 dB to -54 dB at 2.86 GHz. The λ/4 open stubs improve the suppression level by more than 20 dB at the targeted frequencies. The measured results are also shown in Fig. 12(c). Although the measurement of the conventional EBG structure shows no significant peak at 2.4 GHz, the measured data is very similar to the simulated data. The S-parameter characteristics below -40 dB overall were obtained by introducing λ/4 open stubs.

To validate the SSN suppression effect of the λ/4 open stubs, the same technique was used with another conventional EBG structure as shown in Fig. 1(b). In this structure, to improve the 4.4 GHz peak in the measured results, λ/4 open stubs with a length of 9.91 mm and a width of 0.5 mm were attached periodically to both sides of the bridge line between the EBG cells as shown in Fig. 13(a). The simulated and measured results are shown in Fig. 13(b). With the λ/4 open stubs, peak suppression below -60 dB at 4.4 GHz was achieved, which is a greatly improved result. By suppressing the peak at the edge of the stopband through the modified EBG structure, we obtained a much wider suppression bandwidth. Therefore, the modified EBG structure provides not only more stable SSN suppression properties but also a wider stopband than conventional EBG structures.

IV. Conclusion

This paper introduced a spiral-shaped power island structure that effectively suppresses noise around signal ports that generate SSN, and simulated and measured results were reported. The proposed structure had a wide stopband ranging from 0.1 GHz to more than 6 GHz. The proposed structure can be used effectively when few driver ICs are used or when driver ICs are densely located in a small area in a high-speed digital system. We also proposed a new technique to suppress resonance peaks which introduces λ/4 open stubs at specified frequencies in the stopband of a conventional periodic EBG structure. This technique led to more stable SSN suppression than the use of conventional EBG power planes. By suppressing the peaks at the edge of the stopband, we were able to achieve a much wider stopband using the EBG structure modified with λ/4 open stubs. To verify the performance of the proposed structures, extensive three-dimensional electromagnetic simulations were performed using commercially available software. Experimental results that support the simulation data were also presented.

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