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Electromagnetic Interference Analysis of an Inhomogeneous Electromagnetic Bandgap Power Bus for High-Speed Circuits

Jonghyun Cho[1] **and Myunghoi Kim**[2*], ***Member, KIICE***

[1]Rambus Inc., Sunnyvale, CA 94089, USA
[2]Department of Electrical, Electronic, and Control Engineering and Institute for Information Technology Convergence, Hankyong National University, Anseong 17579, Korea

Abstract

This paper presents an analysis of the electromagnetic interference of a heterogeneous power bus where electromagnetic bandgap (EBG) cells are irregularly arranged. To mitigate electrical-noise coupling between high-speed circuits, the EBG structure is placed between parallel plate waveguide (PPW)-based power buses on which the noise source and victim circuits are mounted. We examine a noise suppression characteristic of the heterogeneous power bus in terms of scattering parameters. The characteristics of the dispersion and scattering parameters are compared in the sensitivity analysis of the EBG structure. Electric field distributions at significant frequencies are thoroughly examined using electromagnetic simulation based on a finite element method (FEM). The noise suppression characteristics of the heterogeneous power bus are demonstrated experimentally. The heterogeneous power bus achieves significant reduction of electrical-noise coupling compared to the homogeneous power buses that are adopted in conventional high-speed circuit design. In addition, the measurements show good agreement with the FEM simulation results.

Index Terms: Electromagnetic bandgap (EBG), Electromagnetic interference, Inhomogeneous power bus

I. INTRODUCTION

Because modern electronics are required to support multimedia content and big data analysis, the operating speed and data transfer rate of high-speed circuits has increased substantially. Moreover, the circuit density in packages and boards, have also substantially increased to reduce the form factor of electronic devices. To satisfy design requirements, heterogeneous chips are mounted in a single package on printed electric circuit boards (PCBs), which is called a multi-chip module (MCM) configuration. In MCMs, various chips such as a central processing unit (CPU), memory devices, analog devices, and radio frequency (RF) devices are employed to achieve high performance of the circuit. The heterogeneous chips in MCMs are connected through the interconnects and power buses of a package, and a PCB to transfer data and to deliver power to circuits, respectively. In particular, the power bus design is of importance in MCMs because its main effect is on the overall circuit performance. A power bus can be designed using power planes of arbitrary shape and ground planes. In numerous designs, a polygonal power and ground plane pair is

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***Corresponding Author** Myunghoi Kim (E-mail: mhkim80@hknu.ac.kr, Tel: +82-31-670-5295)
Department of Electrical, Electronic and Control Engineering and Institute for Information Technology Convergence, Hankyong National University, 327 Jungang-ro, Anseong 17579, Korea.

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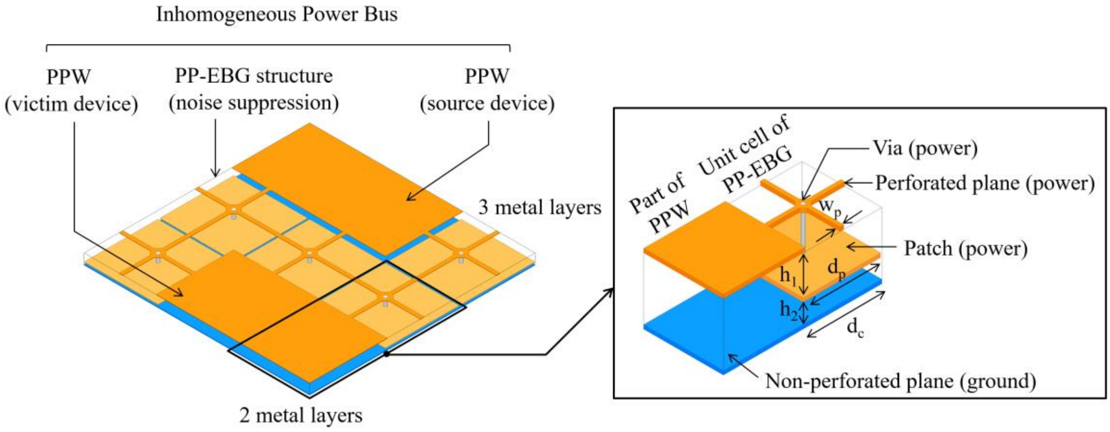


Fig. 1. Heterogeneous power bus using an EBG structure with perforated plane and parallel-plate waveguide.

preferred, and several chips share a single power bus to simplify design and lower cost. However, a power bus shared between a MCM package and a PCB is vulnerable to electromagnetic interference (EMI) [1, 2]. The most significant problem of EMI in a MCM power bus is switching noise. A high-speed switching circuit generates electrical noise that is known as simultaneous switching noise (SSN) and ground bounce noise (GBN). The SSN is easily coupled to other circuits such as RF and analog devices. The coupling of SSN significantly degrades performance of the system. The SSN reduces the signal margin of an eye-diagram and the voltage margin of circuits. Moreover, the sensitivity of RF communication circuits is severely degraded by switching noise. Consequently, overall system performance is significantly influenced by the EMI characteristics of MCMs [1, 2].

To overcome the EMI problem of the MCM power bus, numerous methods of noise suppression have been proposed [3-6]. Because the high-speed circuits induce switching noise in a wideband frequency range, the studies propose methods with broad-bandwidth noise suppression. The suppression of the gigahertz (GHz) noise is particularly crucial for improving the high-speed circuits in MCMs.

To mitigate the GHz noise of the power bus, homogeneous electromagnetic bandgap (EBG) power buses were proposed [3-6]. The EBG structure is a periodic structure with a one or two-dimensional arrangement of unit cells that includes a stepped impedance resonator and a LC resonator. In the homogeneous EBG power bus, the EBG unit cells occupy the entire power bus, which shows wideband suppression and high suppression of the GHz noise. However, the design flexibility of MCM power bus is significantly reduced because the EBG structure interferes with other structures such as the signal interconnects and via-structures. This deteriorates the performance of the EBG structure (the suppression bandwidth is reduced) and a defect mode is generated within the stopband of the EBG structure.

A heterogeneous power bus was recently studied to solve this problem efficiently [7-10]. In this paper, we present a hybrid of a parallel plate waveguide (PPW) and an EBG structure. This was done to increase the design flexibility of the power bus while maintaining the superior characteristics of the EBG structure (i.e., GHz noise suppression). In this paper, Section I provides the introduction and motivations. In Section II, the proposed heterogeneous power bus is described. The noise suppression characteristics and mode analysis are presented in Section III. Experimental validation is shown in Section IV and the conclusions for this work are provided in Section V.

II. DESIGN

The proposed heterogeneous power-bus is a hybrid of the PPW and EBG structure, as shown in Fig. 1. The PPW consists of two conducting layers and a dielectric material, which are used as a power-ground plane pair. A wideband EBG structure was used with a perforated plane (PP) technique. The PP is realized by etching a conducting plane with various shapes [11-14]. In this paper, we adopted a rectangular shape PP due to the simplicity of design and analysis. For a homogeneous EBG structure using a PP technique, the characteristic impedance (Z_o) of the EBG unit cell is increased; thus improving the bandwidth of the noise suppression [11].

The proposed heterogeneous power bus is a compromise solution between design flexibility and noise suppression characteristics. The PPW shows high design flexibility, but the switching noise is easily excited by a PPW mode. The homogeneous EBG structure can substantially suppress the switching noise. In contrast, the use of the EBG structure on an entire board has limitation related to avoiding degradation of the noise suppression characteristics.

The inhomogeneous power bus analyzed herein is illustrated in Fig. 1. The proposed power bus was devised to isolate the electrical noise between a noise source circuit and a noise victim circuit for the improvement of the EMI in MCMs adopted in mobile devices and computing devices. It contains two PPWs and five EBG unit cells. Rectangular PPWs were placed in the noise source and victim circuits. The noise source circuit and the victim circuit can be mounted on the PPWs and electrical power will be delivered into the circuits. To isolate GHz noise passing between a noise source and a victim, the EBG unit cells were arranged between the PPWs. The EBG structure consists of three conducting layers and a dielectric material. Two conducting layers were used for power and the other layer was for a ground. As shown in Fig. 1, the EBG structure using a perforated plane (PP-EBG) contains a perforated power plane, a rectangular patch, and a ground plane. The perforated power plane and the rectangular patch are connected through a via-structure. This means that the power planes of the PPWs and the EBG unit cells are connected so that a direct current (DC) connection can be provided in the proposed heterogeneous power bus.

III. ANALYSIS

To analyze the proposed heterogeneous power bus, the characteristics of the noise isolation, mode analysis, and IR drop were examined.

A. Noise Isolation

The noise isolation of the proposed power bus was characterized using a dispersion diagram based on Floquet's theorem and scattering parameters. In particular, a S_{21} parameter based on a full-wave electromagnetic (EM) simulation was included. Floquet's theorem assumes that unit cells are arranged infinitely. However, the heterogeneous power bus contains a finite and small number of unit cells, which weakens the assumption. Nevertheless, it is valuable to estimate approximately, the noise-suppression qualities of the heterogeneous power bus using Floquet's theorem. To predict accurately the noise suppression characteristics of the heterogeneous power bus, the value of S_{21} parameter must be obtained. In this paper, we acquired the value of the S_{21} parameter using a full-wave simulation with Ansys HFSS. The full-wave simulation provides accurate results, but consumes a great deal of computation time. Thus, the dispersion diagram using Floquet's theorem can be used in the early design stage, and the results later verified with a full-wave simulation.

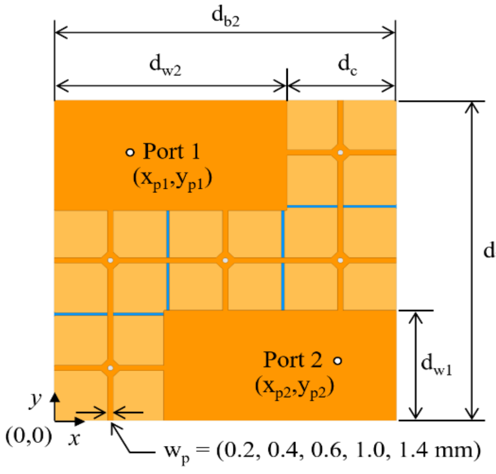


Fig. 2. Heterogeneous power bus with design parameters for noise isolation analysis.

Table 1. Dimensions of the design parameters (unit: mm)

Parameter	Dimension	Parameter	Dimension
w_p	0.2, 0.4, 0.6, 1.0, 1.4	d_{b1}	12.3
d_c	4.1	d_{b2}	12.3
d_p	4.0	x_{p1}	4.7
h_1	0.1	y_{p1}	11
h_2	0.4	x_{p2}	8.9
d_{w1}	4.2	y_{p2}	2.8
d_{w2}	8.2	-	-

The design parameters of the heterogeneous power bus are shown in Figs. 1 and 2. The width of the perforated plane is denoted as w_p. The heights of the EBG unit cell are given as h_1 and h_2. The cell and patch lengths are d_c and d_p, respectively. As shown in Fig. 2, the PPW size is $d_{w1} \times d_{w2}$. The entire power bus size is $d_{b1} \times d_{b2}$. The locations of Port 1 and 2 are indicated by (x_{p1}, y_{p1}) and (x_{p2}, y_{p2}). The origin is located at the lower left corner of the board. The dimensions of the design parameters of the example structure for noise isolation are shown in Table 1. In the analysis, various w_p values were used because w_p is the main design parameter affecting the noise suppression bandwidth [11]. We employed five w_p values (0.2, 0.4, 0.6, 1.0, and 1.4 mm).

The dispersion diagram of the PP-EBG structure adopted in the proposed heterogeneous power bus is illustrated in Fig. 3. The low cut-off frequencies of the dispersion results are highlighted in Fig. 4. The w_p of 1.4 mm shows the low cut-off frequency of 3.42 GHz, while the low cut-off frequency for the w_p of 0.2 mm is 2.45 GHz. The results show that the noise suppression bandwidth increases with decreasing w_p. Thus, the improvement of the noise suppression characteristics can be explained by the characteristically large impedance value of the EBG unit

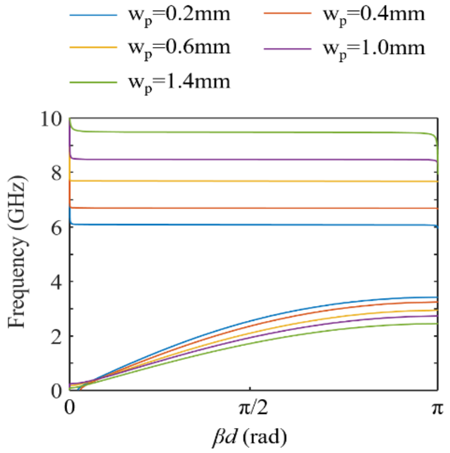


Fig. 3. Dispersion analysis of the PP-EBG structure employed in the heterogeneous power bus.

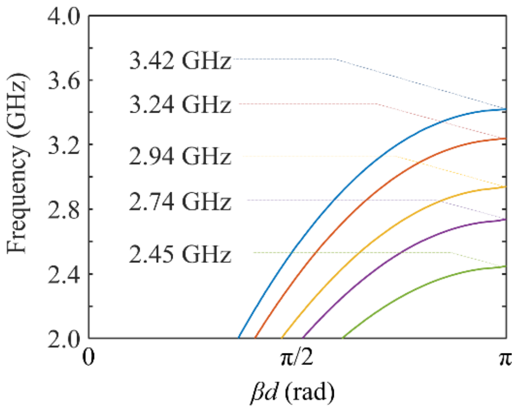


Fig. 4. Highlights of the low cut-off frequencies.

cell, as described in [11]. To investigate a correlation between the dispersion result and the S_{21} parameter, the value of the S_{21} parameter was obtained using a full-wave simulation, as shown in Fig. 5. As with the dispersion results, the noise suppression characteristics improve as the w_p value is reduced. The dispersion result and the S_{21} parameter showed good correlation.

B. Mode Analysis

In Fig. 5, we can observe a resonance peak at approximately 2 GHz, which degrades the noise suppression characteristics. To clearly understand the relevant phenomena, the electric field distributions at two different frequencies were compared. The frequency 2.09 GHz was for the resonance peak, and 4.05 GHz was for the resonance peak suppressed. The w_p value of 0.2 mm was used. In the heterogeneous power bus, two different wave propagation paths were formed, namely one path between the power and ground planes, and one between the patch and ground plane.

As shown in Fig. 6, the electric field of the noise source at the resonance peak (i.e., 2.09 GHz) is easily coupled to the PPW of the noise victim through the paths between the power-ground planes and the patch-ground plane. However, it was observed that the electric field at the resonance suppressed (i.e., 4.05 GHz) was substantially mitigated by the EBG unit cells. The electric field distributions make clear the heterogeneous power bus function considering electromagnetic theory.

C. IR Drop

The proposed heterogeneous power bus employs an EBG structure enhanced by a perforated plane, which narrows the width of the power plane. The proposed power bus was implemented using PCB technology with thin metal (35 µm thick). Thus, the narrow width of the power plane can limit the current capacity performance.

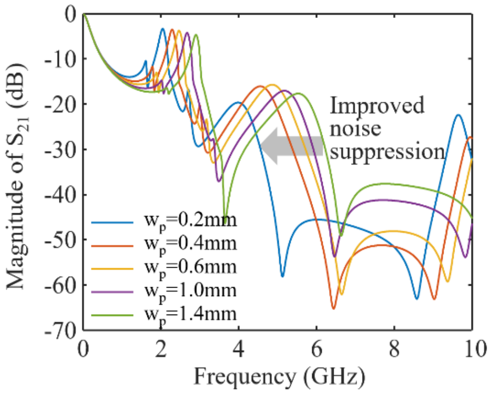


Fig. 5. Simulation results of S_{21} parameters for estimation of the noise suppression characteristics.

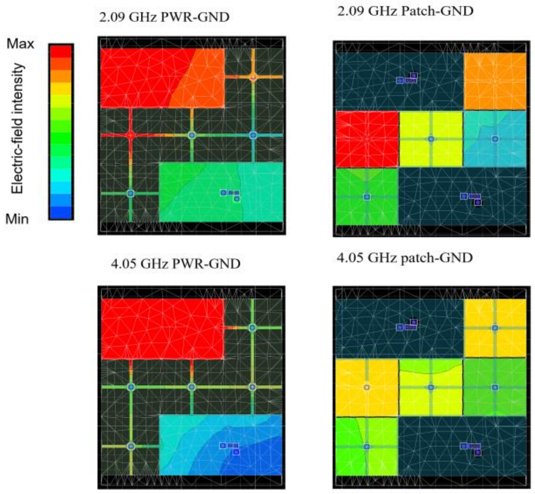
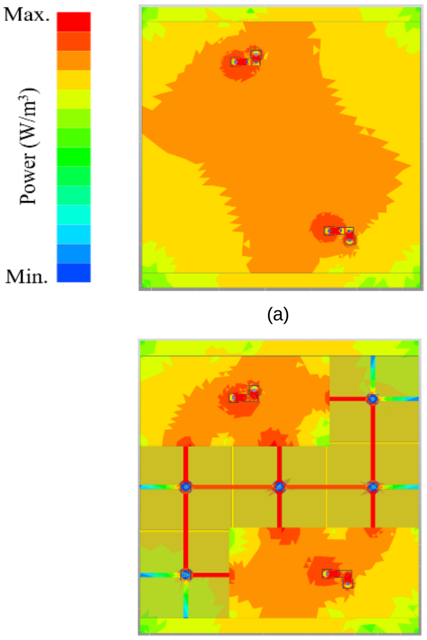


Fig. 6. Electric field distributions for mode analysis.



(a)

(b)

Fig. 7. Power dissipation of (a) homogeneous PPW and (b) heterogeneous EBG power bus.

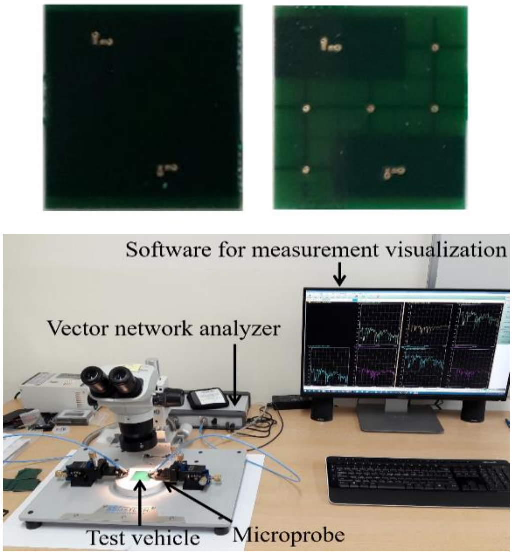


Fig. 8. Test vehicles and measurement setup.

For this reason, the IR drop characteristics had to be analyzed. The IR drop result of the proposed power bus was compared to that of a conventional power bus of a homogeneous PPW. The power distributions are shown in Fig. 7. As expected, the proposed power bus consumes most of the power at the narrow power plane. The power dissipation of the proposed power bus and a conventional PPW-based power bus are 9.84 and 1.76 mW/m^2, respectively. Although the proposed power bus consumes five times more power than the conventional one, the amount of dissipation is far smaller. Therefore, the IR drop problem is not significant for the proposed heterogeneous power bus.

IV. RESULTS

To verify the proposed power bus experimentally, two test vehicles were fabricated: a conventional PPW based power bus (TV A), and the proposed heterogeneous power bus (TV B). We use commercial PCB technology with a plated through-hole-via. The dimensions of the test vehicles were identical to those used in the noise isolation analysis of Section III. The copper and FR-4 were used as the metal and dielectric material, respectively. The S_{21} parameter was measured using a vector network analyzer. The 500 μm pitch GSG microprobes were used to minimize the parasitics of the measurement pads. The measurement setup and the test vehicles are shown in Fig. 8.

As described previously, TV A was the homogeneous power bus with a conventional PPW and TV B was the proposed heterogeneous power bus using a hybrid of the PP-EBG structure and the PPW. The measurements of TV A and TV B are depicted in Fig. 9. The full-wave simulation results are also shown. As seen in the results, the heterogeneous power bus (TV B) significantly suppresses the electrical-noise coupling compared to the conventional homogeneous power bus (TV A). The noise-suppression region of the heterogeneous power bus (TV B) is from 2.2 GHz to at least 10 GHz with regard to the −20 dB suppression level, while the conventional PPW (TV A) exhibits a large amount of noise coupling. Moreover, the measurements and the simulation results showed good agreement. Thus, the inhomogeneous power bus achieved wideband, high-level suppression of the electrical noise in a power bus, thus efficiently solving the EMI problem of high-speed circuits.

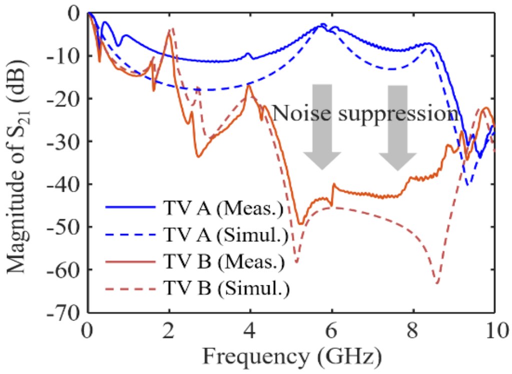


Fig. 9. Comparison of measurements and simulation results for a conventional PPW power bus and a heterogeneous EBG-based power bus.

V. CONCLUSIONS

A heterogeneous power bus employing PP-EBG structure was proposed to solve the EMI problem of high-speed circuits. The inhomogeneous power bus was thoroughly characterized using analysis of the noise isolation, mode distribution, and IR drop. It was verified experimentally that the proposed power bus substantially suppresses electrical-noise coupling compared to a conventional PPW power bus.

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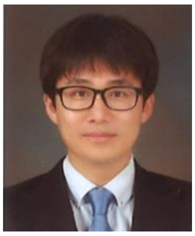
Jonghyun Cho

received B.S., M.S., and Ph.D. degree in electrical engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2008, 2010, and 2013, respectively. He also worked at KAIST as a postdoc until the end of 2014. During the periods at KAIST, he successfully performed several projects, which include 3D-IC TSV modeling, silicon and glass interposer design, and POP PKG design for mobile phone AP. He worked at Missouri S&T EMC laboratory as a visiting assistant research professor from 2015 t0 2017. In 2017, He is working at Rambus Inc., CA, USA. His current research topics are SI/PI/RFI issues on system including chip, PKG, PCB, 2.5D and 3D-IC, and WPT.



Myunghoi Kim
received B.S., M.S., and Ph.D. degrees in electrical engineering at the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2003, 2005, and 2012, respectively. From 2005 to 2008, he was a researcher for signal integrity and EMC analysis of the missile electronic systems in Agency for Defense Development (ADD), Daejeon, Korea. He was a Visiting Researcher at Silicon Image, Inc., Sunnyvale, CA, in 2011. He was a senior member of engineering staff at Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea, from 2012 to 2015. In 2015, he joined the Department of Electrical, Electronic and Control Engineering, Hankyong National University, Anseong, Korea, as an assistant professor. He is a senior member of IEEE and the member of IEICE, KIMST and KIICE. His current research interests include signal and power integrity for high-speed packages and PCBs, electromagnetic shielding analysis using a reverberation chamber, and slow-wave/electromagnetic bandgap structures for EMI/EMC.