Ultrawideband Suppression of Ground Bounce Noise in Multilayer PCB Using Locally Embedded Planar Electromagnetic Band-Gap Structures

Long Li, *Member, IEEE*, Qiang Chen, *Member, IEEE*, Qiaowei Yuan, and Kunio Sawaya, *Senior Member, IEEE*

***Abstract*—A novel uniplanar compact electromagnetic band-gap (EBG) structure is proposed for ultrawideband (UWB) suppression of ground bounce noise (GBN) in multilayer PCB. The power plane integrates the features of L-shaped bridges and slits (LBS), which can suppress the GBN at lower and higher frequencies, respectively, without using hybrid periods cascading structures. The GBN suppression bandwidth is broadened from 432 MHz to 15 GHz covering almost the whole noise band for UWB applications. A locally embedded LBS-EBG structure in power plane is proposed to improve signal integrity (SI). Full-wave simulation and measurement are performed to verify the high performance.**

***Index Terms*—Electromagnetic band-gap (EBG), ground bounce noise (GBN), locally embedded, multilayer printed circuit board (PCB), signal integrity.**

I. INTRODUCTION

WITH the trends of mix-signal system integration, high-speed microprocessors, radio frequency (RF) circuits, memory, sensors, and optical devices, etc., are required to be integrated into a tight module, which is known as "system on package". The ground bounce noise (GBN) [1], also known as simultaneous switching noise (SSN), on the power/ground planes is becoming one of the major bottleneck for designing the high-speed circuits in multilayer printed circuit board (PCB). As the systems operate toward higher frequency range, the GBN will excite the resonance modes of the parallel-plate waveguide structure between power and ground planes, which behave as radial waves and travel outwards from noise source to the edges of circuit board. Some portion of the energy is reflected inwards affecting the signal integrity (SI) and some part is radiated into free-space causing the electromagnetic interference (EMI) problems [2]. Especially in ultrawideband (UWB) communication technology, since the maximum signal power is limited to a very low level, any noise from digital circuits could destroy the functionality of RF circuits and cause system failure.

Some typical ways [3], such as adding decoupling capacitors, splitting the power and/or ground planes, and using the isolation moat, have been proposed to eliminate the GBN, but they are not effective above 1 GHz. Recently, a new idea for eliminating the GBN was introduced by using electromagnetic band-gap (EBG) structures [4], [5]. There are many researches focused on EBG structure design to broaden the stopband for high efficient GBN suppression [6]–[11].

In this letter, a novel uniplanar compact EBG structure which integrates L-bridged EBG structure with slits is proposed for ultra-wideband GBN suppression in multilayer PCB. The GBN suppression bandwidth is broadened to cover from 432 MHz to 15 GHz without using cascading different period structures. To improve the SI, a locally embedded EBG structure in power plane is used. S-parameters for multiport network and E-field distribution on each layer are investigated. The distinctive behavior of the new EBG power plane in ultra-wideband suppression of the GBN is validated by simulations and measurements.

II. DESIGN OF NEW L-BRIDGED EBG STRUCTURE WITH SLITS

To filter out GBN propagating within the power/ground planes while providing a low-impedance path for DC current on each layer, a two-layer EBG embedded power plane structure is used, and the ground plane is kept continuous for SI view. Fig. 1(a) shows the proposed L-shaped bridges with slits (LBS) EBG power/ground planes design. The unit cell of the EBG power plane consists of one square patch with four narrow slits inserted at the boundary of the patch, and four L-shaped bridges on each side of the patch [11]. The unit cell of the LBS-EBG and its corresponding notations of parameters are shown in Fig. 1(b).

The key feature of this new structure is an integration of L-bridges with slits. Compared to the traditional UC-EBG structure with straight bridges [5], the L-shaped bridges not only improve the inductance between two neighboring patches so that they can suppress the noise at lower frequencies, but also keep signal quality acceptably well [6]. Compared to the previous L-bridged EBG structures, the narrow slits inserted at the boundary of the patch change the flow paths of currents. Due to the slits perturbation, the resonant mode of the square patch will be split so that they can suppress the noise at higher frequencies. As a result, the geometry of the slit and bridge can be designed properly based on the requirement of suppression bandwidth.

III. ULTRAWIDEBAND GBN SUPPRESSION

To demonstrate the effectiveness of the LBS-EBG power plane, we consider a design of a two-layer PCB with the dimension 90 mm × 150 mm consisting of 3×5 unit cells.

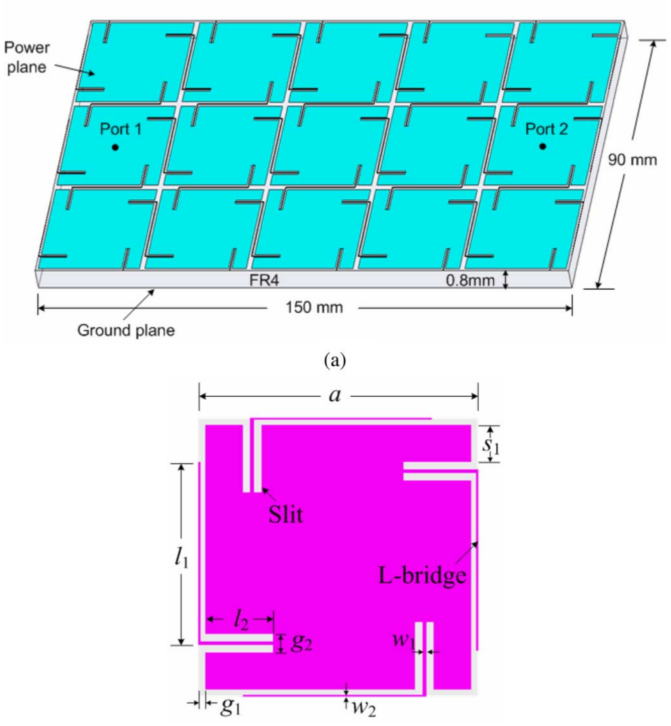
Manuscript received August 05, 2008; revised October 25, 2008. First published November 17, 2008; current version published July 28, 2009. This work is supported in part by the National Natural Science Foundation of China under Contract 60601028 and by the JSPS Postdoctoral Fellowship of Japan.

L. Li was with Tohoku University, Sendai, 980-8579, Japan. He is now with the School of Electronic Engineering, Xidian University, Xi'an, 710071, China (e-mail: lilong@mail.xidian.edu.cn; lilong@ecei.tohoku.ac.jp).

Q. Chen, Q. Yuan, and K. Sawaya are with the Department of Electrical and Communication Engineering, Tohoku University, Sendai, 980-8579, Japan (e-mail: chenq@ecei.tohoku.ac.jp; qwyuan@ecei.tohoku.ac.jp; sawaya@ecei.tohoku.ac.jp).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LAWP.2008.2009363



(a)

(b)

Fig. 1. (a) Uniplanar compact EBG structure with L-bridges and slits (LBS) showing the location of the ports used for S_{21} parameter measurements. (b) Unit cell showing the L-bridges with slits and dimensions.

The substrate dielectric is FR4 with a relative permittivity of 4.4 and a loss tangent of 0.02. The thickness of the substrate is 0.8 mm and the thickness of the copper foil is 0.035 mm. The corresponding parameters are $a = 30$ mm, $w_1 = 0.2$ mm, $w_2 = 0.1$ mm, $l_1 = 19.7$ mm, $l_2 = 7.25$ mm, $g_1 = 0.75$ mm, $g_2 = 1.0$ mm, and $s_1 = 4.0$ mm. Here each slit has an equal length. For a special design, four inserted slits of different lengths can be used. Performance of the EBG structure can be characterized using S-parameters. The S_{21} parameter between two ports lying across several patches is sufficient to show the frequency band-gap of the structure, as shown in Fig. 1.

Fig. 2 shows the measured and simulated $|S_{21}|$ for the designed LBS-EBG power/ground planes. The insertion loss of the reference board with both power and ground planes being solid is also presented in this figure for comparison. The HFSS of Ansoft Corporation was used to simulate the GBN behavior of the structure. Good agreement between the measurement and simulation is obtained. An ultra-wideband suppression is observed starting at approximately 432 MHz and extending to 15 GHz. The definition of bandwidth adopted here is the continuous frequency range over which $|S_{21}|$ is lower than -40 dB.

Compared with the conventional UC-EBG power plane (which has the same substrate and periods of 3×5 as Fig. 1, and the element parameters are $a = 30$ mm, $w_1 = 0.2$ mm, $l_2 = 7.25$ mm, $g_1 = 0.75$ mm, $g_2 = 1.0$ mm, but $s_1 = 13.75$ mm and $w_2 = l_1 = 0$) [5] and the old L-bridged EBG power plane (other parameters are kept the same as Fig. 1 except that $l_2 = g_2 = 0$) [6], the proposed LBS-EBG power plane can suppress the GBN from lower frequency (432 MHz) to higher frequency (15 GHz), which can cover the whole UWB communication frequency range (from 3.1 to 10.6 GHz), as shown in Fig. 3. According to the symmetry of the structure, the LBS-EBG power plane can omnidirectionally eliminate the GBN on the power/ground planes.

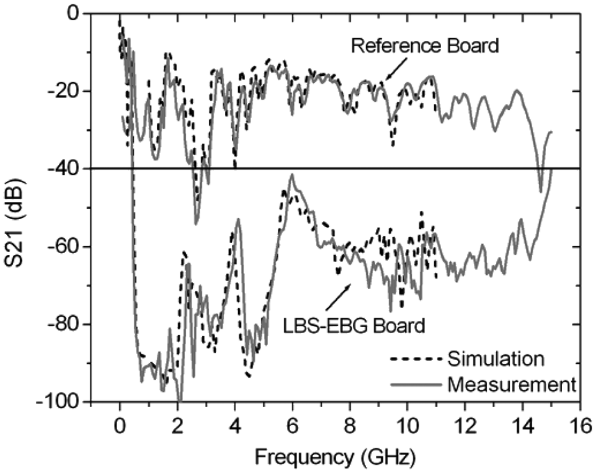
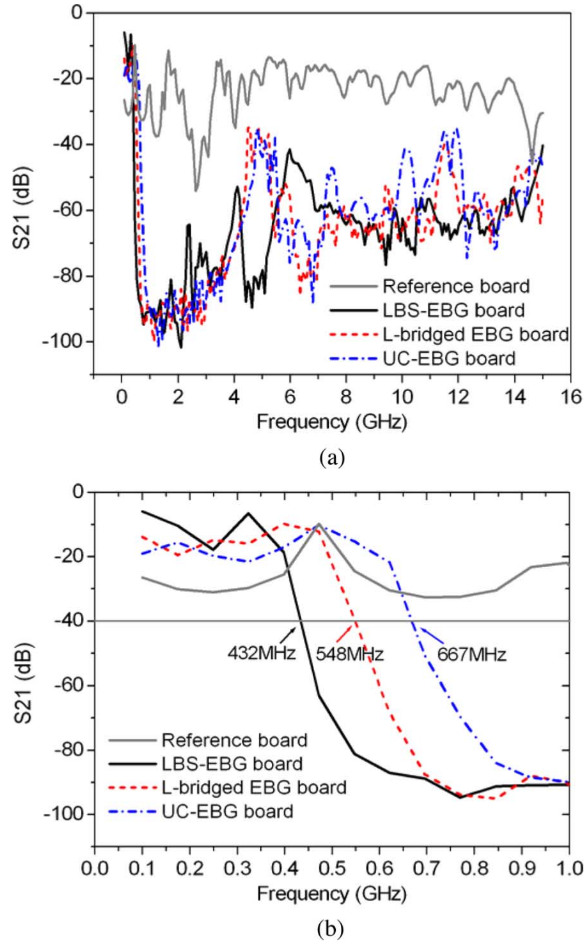


Fig. 2. Comparison of $|S_{21}|$ between the LBS-EBG board and the reference board by the numerical simulation and the measurement.



(a)

(b)

Fig. 3. Measured insertion losses ($|S_{21}|$) of the proposed LBS-EBG, the conventional UC-EBG, and the old L-bridged EBG power planes. (a) Whole frequency characteristics. (b) Lower frequencies characteristics.

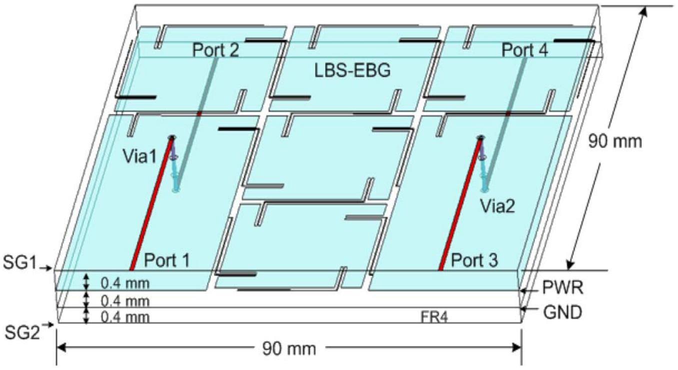


Fig. 4. Four-layer PCB structure with transmission lines transition between the locally embedded LBS-EBG power plane and solid ground plane.

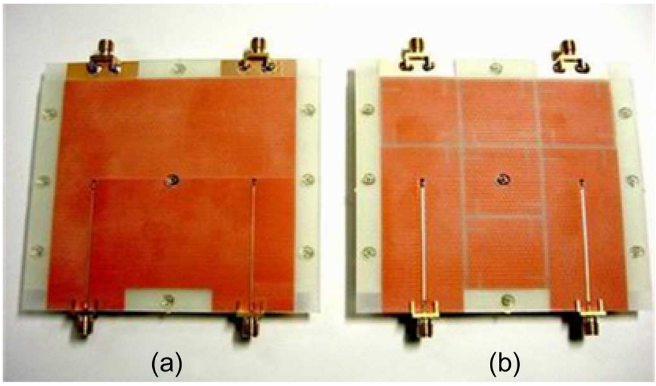
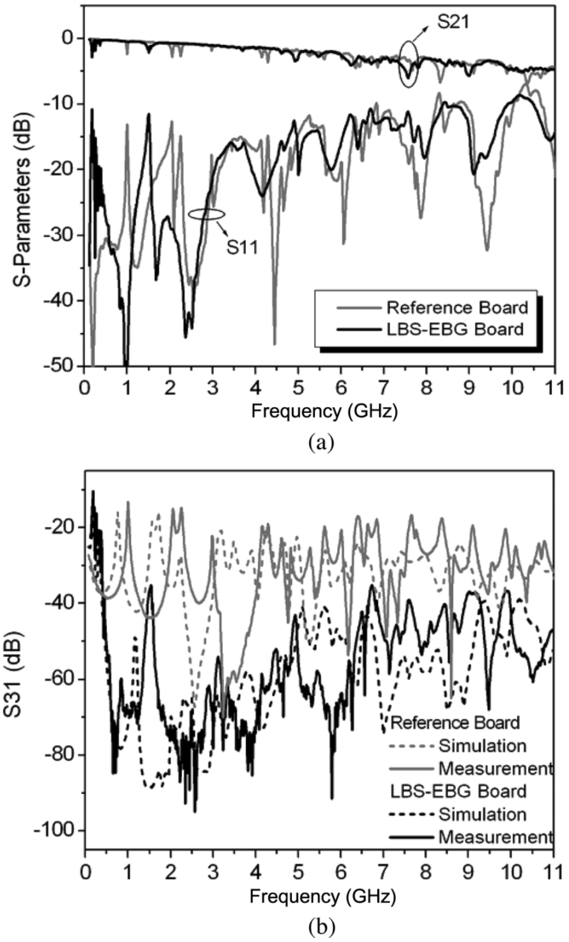


Fig. 5. Fabricated multilayer PCBs. (a) Reference board and (b) LBS-EBG board.



(a)

(b)

Fig. 6. Comparison of S-parameters of multilayer reference board and LBS-EBG board: (a) measured S11 and S21, (b) simulated and measured S31.

IV. LOCALLY EMBEDDED LBS-EBG IN MULTILAYER PCB

Fig. 4 shows a four-layer PCB structure with two transmission lines passing from the top layer (SG1) to the bottom layer (SG2), with two via transitions between the power plane (PWR) and solid ground plane (GND). Although the proposed design of power/ground planes shows excellent performance on eliminating the GBN at broadband frequency ranges, the signal integrity problem is inevitable for the proposed EBG structure because of the discontinuity of power plane. The SI problem can be solved by adding another ground plane above the power plane [5], or using stitch capacitors [10]. Here, a scheme of locally-embedded EBG elements is adopted to improve the SI. The local regions of power plane corresponding to signal traces are still kept continuous, and other regions are replaced with LBS-EBG elements. All local regions can be connected by L-bridges. The traces are designed as 50 Ω for the transmission signal. The parameters of LBS-EBG elements are the same as those in Fig. 2 except that the thickness of substrate here is 0.4 mm.

The LBS-EBG board and a reference board with solid power and ground planes were fabricated and shown in Fig. 5. The four-port S-parameters for the two kinds of boards are simulated and measured. Fig. 6(a) and (b) show the comparison of measured S-parameters for the reference board and the locally embedded LBS-EBG board.

It is found from Fig. 6 that the signal trace passes through via will couple energy to the power bus and propagate between the power and ground planes with multi-reflections. On the contrary viewpoint, while GBN occurs and propagates outward along power bus, some power energy is reflected and some power will be coupled to signal trace by through-hole-via. In Fig. 6(b), S31, which is almost the same as S41, shows that the GBN coupling can be effectively suppressed by using LBS-EBG locally embedded in power plane. The characteristics of S11 and S21 show that the energy suppressed is mainly transported from port 1 to port 2, as expected.

Figs. 7 and 8 show the normalized E-field distribution on each layer of reference and LBS-EBG boards, respectively. It can be seen from Fig. 7 that there are strong resonance modes of the parallel-plate waveguide structure between power and ground planes excited by GBN in reference board. But only a local resonance mode exists in LBS-EBG board due to a locally embedded scheme. The GBN is hardly coupled to signal traces in other blocks constituting system, as shown in Fig. 8. Furthermore, compared to a wholly embedded EBG structure of 3 by 3 unit cells [5], the signal distortion should be smaller using a locally embedded LBS-EBG structure. Fig. 9 shows the residual power coefficients which represents radiated power from the multilayer PCB when port 1 is excited and other ports are terminated by 50 Ω loads. It can be found that the EMI problem can be reduced at low frequency, but still exists at high frequency even if using our proposed structure. One possible solution is to setup high-loss magnetic materials around the edge of the board

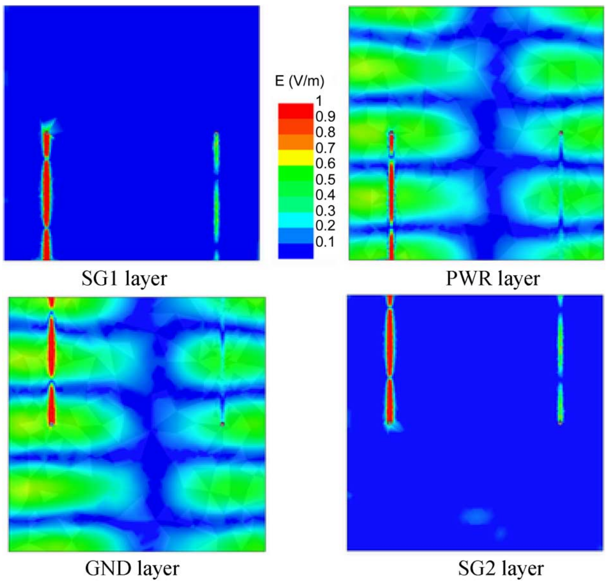


Fig. 7. Normalized E-field distribution on each layer of reference board at 3.3 GHz.

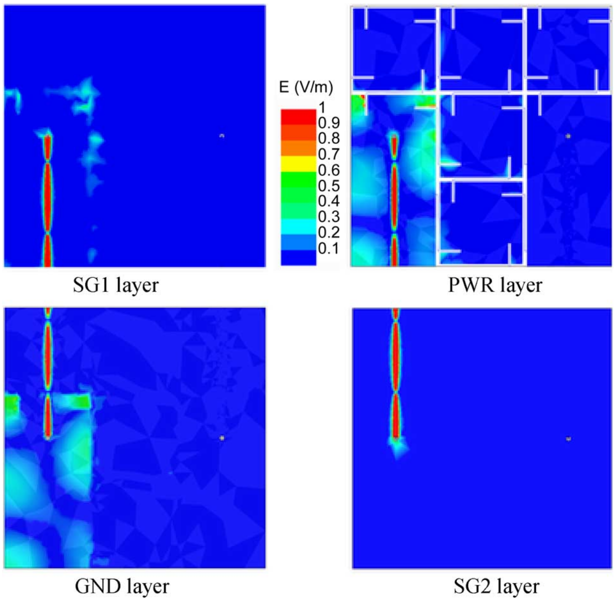


Fig. 8. Normalized E-field distribution on each layer of LBS-EBG board at 3.3 GHz.

to reduce EMI. The dashed line shows the residual power coefficient of the other reference board without vias which has only two transmission lines on the top surface with the same length as the total length including top and bottom surfaces of the reference board shown in Fig. 5(a). So the dashed line represents the radiation power coefficient from transmission lines themselves without GBN.

V. CONCLUSION

In this letter, a novel LBS-EBG power plane has been proposed for ultrawideband GBN suppression in multilayer PCB. The GBN suppression bandwidth is broadened from 432 MHz to 15 GHz covering almost the whole noise band and for UWB technology applications. The locally embedded LBS-EBG structure is adopted to improve the SI problem, which keeps the power plane corresponding to signal traces still continuous. The excellent performance of LBS-EBG power plane has been demonstrated both by simulation and measurement.

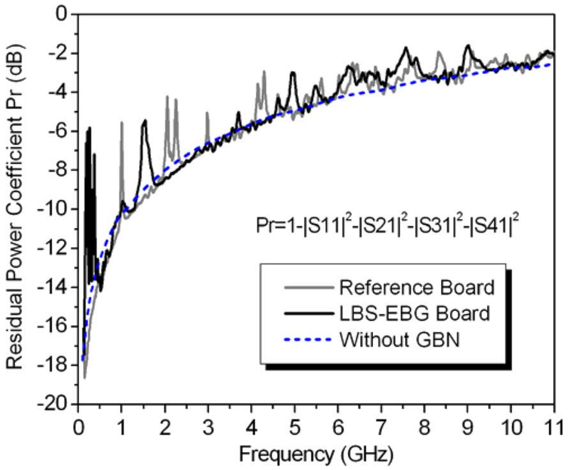


Fig. 9. Comparison of residual power coefficients from reference board and LBS-EBG board. The dashed line represents the radiation power coefficient from transmission lines themselves without GBN.

REFERENCES

[1] S. Van Den Berghe, F. Olyslager, D. De Zutter, J. De Moerloose, and W. Temmerman, "Study of the ground bounce caused by power plane resonances," *IEEE Trans. Electromagn. Compat.*, vol. 40, no. 2, pp. 111–119, May 1998.

[2] T. L. Wu, S. T. Chen, J. N. Huang, and Y. H. Lin, "Numerical and experimental investigation of radiation caused by the switching noise on the partitioned dc reference planes of high speed digital PCB," *IEEE Trans. Electromagn. Compat.*, vol. 46, no. 1, pp. 33–45, Feb. 2004.

[3] V. Ricchiuti, "Power-supply decoupling on fully populated high-speed digital PCBs," *IEEE Trans. Electromagn. Compat.*, vol. 43, pp. 671–676, Nov. 2001.

[4] T. Kamgaing and O. M. Ramahi, "A novel power plane with integrated simulataneous switching noise mitigation capability using high impedance surface," *IEEE Micro. Wireless Compon. Lett.*, vol. 13, pp. 21–23, Jan. 2003.

[5] T. L. Wu, Y. Y. Lin, C. C. Wang, and S. T. Chen, "Electromagnetic bandgap power/ground planes for wideband suppression of ground bounce noise and radiated emission in high-speed circuits," *IEEE Trans. Microw. Theory Tech*, vol. 53, no. 9, pp. 2935–2942, Sep. 2005.

[6] T. L. Wu, C. C. Wang, Y. H. Lin, T. K. Wang, and G. Chang, "A novel power plane with super-wideband elimination of ground bounce noise on high speed circuits," *IEEE Micro. Wireless Compon. Lett.*, vol. 15, no. 3, pp. 174–176, Mar. 2005.

[7] X. H. Wang, B. Z. Wang, Y. H. Bi, and W. Shao, "A novel uniplanar compact photonic bandgap power plane with ultra-broadband supprssion of ground bounce noise," *IEEE Micro. Wireless Compon. Lett.*, vol. 16, no. 5, pp. 267–268, May 2006.

[8] J. Qin and O. M. Ramahi, "Ultra-wideband mitigation of simultaneous switching noise using novel planar electromagnetic bandgap structures," *IEEE Micro. Wireless Compon. Lett.*, vol. 16, no. 9, pp. 487–489, Sept. 2006.

[9] M. S. Zhang, Y. S. Li, C. Jia, L. P. Li, and J. Pan, "A double-surface electromagnetic bandgap structure with one surface embedded in power plane for ultra-wideband SSN suppression," *IEEE Micro. Wireless Compon. Lett.*, vol. 17, no. 10, pp. 706–708, Oct. 2007.

[10] S. H. Joo, D. Y. Kim, and H. Y. Lee, "A S-bridged inductive electromagnetic bandgap power plane for suppression of ground bounce noise," *IEEE Micro. Wireless Compon. Lett.*, vol. 17, no. 10, pp. 709–711, Oct. 2007.

[11] L. Li, Q. Chen, and K. Sawaya, "Ultra-wideband suppression of ground bounce noise using novel uniplanar compact electromagnetic bandgap structure," in *Proc. 2008 IEEE AP-S USNC/URSI Symp.*, San Diego, CA, Jul. 5–12, 2008.