Signal Integrity Analysis of High Speed Interconnects In PCB Embedded with EBG Structures

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Abstract - This paper brings out a novel method for reducing Near end and Far end Crosstalk using Electromagnetic Band Gap structures (EBG) in High Speed RF transmission lines. This work becomes useful in high speed closely spaced Printed Circuit Board (PCB) traces connected to multi core processors. By using this method, reduction of -40dB in Near-End Crosstalk (NEXT) and -60 dB in Far End Crosstalk (FEXT) is achieved. The results are validated through experimental measurements. Time domain analysis is performed to validate the signal integrity property of coupled transmission lines.

Keywords: High speed interconnects, Electromagnetic Band Gap Structures (EBG), Near-End Crosstalk (NEXT), Far-End Crosstalk (FEXT), Signal Integrity (SI), Eye Pattern (EP), Time Domain Reflectometry (TDR)

1. Introduction

Signal integrity (SI) issues gain importance due to increasing speeds and packing densities. High packing densities require decreasing trace width and trace spacing in printed circuit board (PCBs), connected to Multicore processors. One of the major issues is the crosstalk between traces. The trend in these digital systems is to reduce the power supply voltage levels and to increase the clock frequencies, making the noise propagation and coupling along the boards a critical issue. A vast number of available scientific literature have proposed design methodologies to achieve simultaneous switching noise (SSN) mitigation by means of embedded 2-D or 3-D electromagnetic band gap structures (EBGs). This technique was first introduced [1] and allowed suppression of SSN in multilayer PCBs.

EBG structures have contributed to the growing interest in microwave and MMIC applications because they are simple to manufacture and easy to monolithically integrate with other circuits. More efficient and low-cost 2-D EBGs were introduced [2-4]. In these configurations, the power or ground layers are directly patterned with patches in order to provide stop bands over a broader frequency range. Novel geometries were introduced in [5-8] with the specific goal of simultaneously broadening and lowering the frequency range for the noise isolation and suppression. Recently some attention has been addressed to the

performance of the signal link paths in the presence of signal reference planes of EBG types [9, 10].

Mutual coupling effect is mitigated by using EBG structures [11] by properly identifying the location and determining the dimensions of the unit cell EBG and more than 20 dB mutual coupling suppression of perpendicular transmission line is observed. For efficient EMI reduction in multilayer PCB, cascaded structure of EBG [12] is implemented. Different types of Defective ground structures [13] are used to reduce the crosstalk level in PCBs. A novel array method of EBG unit cells located partially on power / ground planes is proposed for multilayer PCBs and packages [15].

Most of the modern electronic equipments operate in the frequency range from 0.9 to 6 GHz [20]. Reference [16] is also dealing with the reduction of SSN in the frequency range between 0.9 to 4 GHz. Thus analysis and suppression of mutual coupling in this is important. Multilayer structures are used for reducing the mutual coupling instead of using single layer for space constraint.

To improve Signal and power integrity in multilayered PCB, complementary split-ring-resonators are utilized [22]. These structures provide a compact and embeddable geometry formed in the Power bus structure to remove the resonance that hinders the signal transfer from one layer to another.

Crosstalk between traces is reduced by placing Via fences [23], Serpentine Guard traces [24], Serpentine Guard trace with vias and rectangular resonators [25] in between the traces. Defective microstrip lines structures [26] have been used for the reduction of crosstalk. The proposed work does not have any elements in between the traces, instead uses Electromagnetic Band gap in the other layer. The comparison of geometrical parameter and the level of mutual coupling reduction between traces are

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Table 1. Comparison with the existing techniques

Reference	Technique adopted	Thickness of the substrate (mm)	Width of the line (mm)	Spacing between the lines (mm)	Length of the line (mm)	Mutual coupling reduction (mm)
[23]	Via fences	0.508	0.97	7.57	100	-30.0
[24]	Serpentine guard trace	0.2	0.35	0.9	500	-27.86
[20]	Serpentine guard trace with vias	0.18	0.3	0.9	101.6	-27.9
[25]	Rectangular shaped resonators	1.6	3	9	50	-29.85
[26]	Defective micro stripline structures	0.762	2	1.67	10	-35.0
Our work	Electromagnetic band gap structures	0.8	3	0.5	200	-40.0

given in Table 1.

This paper introduces a novel method of placing EBG to reduce NEXT and FEXT in the frequency range of 3-4GHz. This method finds an application in the PCB traces connected to new generation processors working on this frequency range. To reduce the mutual coupling between the traces, two types of EBG structures have been placed in array type configuration. As there are no extra structures in between the lines to reduce coupling noise, this method gives extra freedom to the system level designer to arrange the traces. The conventional method of reducing the mutual coupling between traces is by keeping the separation between parallel traces to be thrice the trace width. This is termed as 3-W rule [14]. In our proposed work the traces were separated by 0.5mm which is 1/6 of the width of the trace.

The paper is organized as follows. Section 2 contains Characterization of EBG structures. The proposed crosstalk reduction method using Square and Circular Mushroom EBG structures have been modeled and simulated in Section 3. In Section 4, simulation and the measurement results of the proposed structures are given. Time domain analysis in terms of eye diagram characterization, rise time measurements and Time domain reflectometry of the EBG structures are presented in Section 5. Section 6 concludes the paper.

2. EBG Structure Characterization

Electromagnetic band gap (EBG) structures forbid the propagation of electromagnetic waves within a particular band. Each unit lattice of these structures can be roughly modeled by parallel LC resonant circuits, which can be employed to improve the designs of filters, reflectors, amplifiers, and patch antennas. Design equations of a Mushroom type EBG structure [19] are given as follows:

$$\text{Resonant Frequency } f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

$$C = \frac{w\epsilon_o(1+\epsilon_r)}{\pi} \cosh^{-1} \frac{w+g}{g} \quad (2)$$

$$L = 2 \times 10^{-7} h \left[\ln \left(\frac{2h}{g} \right) + 0.5 \left(\frac{2r}{h} \right) - 0.75 \right] \quad (3)$$

The resonant frequency, capacitance and inductance for the mushroom type EBG are given in Eqs. (1) - (3) where the 'w' is the width of the EBG, 'g' is the spacing between EBG, 'h' is the substrate thickness, 'r' is the radius of the via and the substrate permittivity is ' ϵ_r '. The important parameters for the EBG array are the side/radius of the EBG, the gap between the EBGs, height of the substrate and the radius of the via. L value can be found out by solving Eq. (1) for $f_0=3.5\text{GHz}$ and assuming C value. Solving Eq. (2) by using C value and fixing 'g' along with a substrate of Known permittivity we can find out 'w' which corresponds to side/ radius of the EBG structure. By solving Eq. (3) using the obtained L value and the known substrate height, the radius of the via can be found out.

The geometrical parameters of the EBG structure are: $w=9.9\text{mm}$, $g=0.2\text{mm}$, $r=0.5\text{mm}$ and the substrate thickness $h=0.8\text{mm}$ with the relative permittivity of the substrate is 4.3 at 3.5 GHz. The equivalent inductance and capacitance values obtained are 41.3 nH and 0.053pF respectively.

Mushroom type Square and Circular EBG structures and the method of characterizing these structures are shown in Fig. 1. To apply these EBG structures to actual PCBs, it is necessary to quickly and accurately compute the stop band frequencies of interest in the design stage. First the stop band characterization is done using equivalent circuit method.

Using the Eqs. 1-3 the equivalent circuit is designed and the S-parameters were found out. Fig. 2 shows the band stop characterization for the square and circular mushroom EBG structures.

The EBG structures were characterized by commercial EM software (CST). The unit cell is designed and simulated using Eigen mode solver. The stop band response obtained from the simulation is given in Table 2.

Fig. 1. Mushroom type EBG structures: (a) Square Circular; (c) Suspended line method for characterizing EBG

Fig. 2. Transmission coefficient of different Mushroom EBG structures

Table 2. Band Gap By Eigen Mode Solver

Type of EBG	Mode 1(GHz)	Mode 2(GHz)	Band gap(GHz)
Square	2.66	4.30	1.63
Circular	2.76	3.93	1.17

From Table 2 we can find that the stop band frequencies of unit cell Square mushroom EBG is in the frequency range 2.7-4.3 GHz and for Circular mushroom EBG it is 2.8-4.5 GHz.

3. Proposed Crosstalk Reduction Method

Coupled line -

The density of interconnects on a PCB layer is mainly limited by the crosstalk levels between adjacent interconnects. In order to reduce the magnitude and effect of crosstalk between adjacent interconnects, many design rules and techniques have been widely adopted by high-speed PCB designers. The trace to trace spacing of 3-W rule is mostly followed by high-speed PCB designers.

The main aim of our work is to reduce the spacing between the interconnects from three times the trace width (3-W) to one-sixth ($1/6 W$) of the trace width so as to achieve compactness in PCB. The proposed structure [18] of two closely spaced transmission lines are shown in Fig. 3. The dimensions of the PCB are of Length ' L ' = 200mm and Width ' W '=50mm. The traces in the PCB are of 200mm and the width ' W_t ' of 2.99mm for trace impedance of 50 Ω . The spacing between the lines ' S ' is 0.5mm ($1/6 W$). The thickness of the line is 35 μ m. The substrate material is FR4 with relative permittivity of 4.3 and loss tangent 0.0023.

Fig. 3. PCB with the source and victim traces with port numbers

3.1 Method 1. Square Mushroom EBG

The analyses of crosstalk reduction were done by embedding the EBG structures in array type configuration. The behavior of the structure is probed at 4 points by means of discrete ports as shown in Fig.3 and simulation is done by using CST Microwave Studio solver. The S-parameters namely, $|S_{31}|$ -Near End Crosstalk and $|S_{41}|$ -Far End Crosstalk were computed and with the coupled microstrip lines placed at a spacing of 0.5mm.

Fig. 4 shows the proposed three layer structure. On the top of the Layer 1, EBG structures of mushroom types discussed above are placed partially and microstrip transmission lines are placed on Layer 2. In the square configuration the NEXT and FEXT for different iterations are given in Fig. 5 (a) and (b) respectively.

Fig. 4. Proposed three layer PCB structure with Mushroom type square EBG

(a)

(b)

Fig. 5. S-parameters Vs frequency: (a) $|S_{31}|$; (b) $|S_{41}|$

The band of interest is 3.1 to 3.9 GHz used in high speed PCB traces connected to Multi core processors. When the configuration is 3x3, the reduction in NEXT and FEXT are not achieved. Hence, the array size have been increased and the reduction of crosstalk has been observed for the 4x4 and 5x5 arrays. Hence 4x4 array type was chosen to reduce fabrication complexity.

3.2 Method 2: Circular Mushroom EBG

The proposed structure is given in Fig. 6. The analysis was performed by increasing the number of EBGs and corresponding responses were observed.

These NEXT and FEXT values are shown in Fig. 7(a) and (b) respectively. For the 2x2 and 2x3 arrays, a gradual reduction in the crosstalk is achieved. And when it is 2x4

Fig. 6. Proposed three layer PCB structure with Mushroom type circular EBG

Fig. 7. Simulated results S-parameters frequency: (a) $|S_{31}|$ (b) $|S_{41}|$

array, good response is achieved for the required band. This response is nearly equal to 4x4 square EBG responses. So this is selected as another method for reducing crosstalk. The 2x4 circular EBG configuration reduces the fabrication complexity even more.

4. Fabrication and Measurement

The optimized square and circular configuration were fabricated and measured.

4.1 Square Mushroom EBG

From the above simulation results the optimum performance is obtained by 4x4 square mushroom EBG structure. The structure with 4x4 array of square mushroom EBG is fabricated as shown in Fig. 8. The measured results of the Near End and Far end crosstalk are given in Fig. 9.

Fig. 8. Fabricated prototype PCB with coupled microstrips and square mushroom EBG

Fig. 9. Measured results S-parameters Vs frequency: (a) $|S_{31}|$; (b) $|S_{41}|$

4.2 Circular Mushroom EBG

From the simulated results 2x4 array gave better performance. The structure with 2x4 array of circular mushroom EBG is fabricated as shown in Fig. 10.

Fig. 10. Fabricated prototype PCB with coupled microstrips and circular mushroom EBG

The simulated and the measured results of Near End and Far End Crosstalk of circular EBG are given in Fig. 11.

Fig. 11. Measured results S-parameters Vs frequency: (a) $|S_{31}|$; (b) $|S_{41}|$

Table 3. Frequency range of EBG structures for S-parameters below -15dB

Frequency	Square mushroom EBG		Circular mushroom EBG	
	Near end crosstalk	Far end crosstalk	Near end crosstalk	Far end crosstalk
Lower frequency (GHz)	3.23	3.42	3.00	3.37
Upper frequency (GHz)	4.12	4.23	4.89	4.0
Bandwidth (GHz)	0.89	0.81	1.89	0.63

The coupling level from Port1 to Port 3 which is the Near end crosstalk and from Port1 to Port4 which is the Far end crosstalk is reduced. The performances of the EBG structures are given in Table 3.

From the above results the crosstalk reduction over a wide band is achieved.

Fig. 12 shows the surface current distribution over the coupled lines for without EBG, with square EBG and Circular EBG at 3 GHz. It can be observed that the current distribution over the near end and far end ports are getting reduced with the presence of EBG structures.

Fig. 12. Surface Current distribution at 3 GHz: (a) Without EBG; (b) Square EBG; (c) Circular EBG

5. Time Domain Analysis

The Signal Integrity analysis explains the signal purity and the jitter associated with the signal. The highest data rate that can be sent through the interconnects either referenced to ground or EBG can be obtained from Signal Integrity analysis. Although the proposed model reduces the NEXT and FEXT levels over a wide frequency range, its effect on propagating a digital signal needs to be analyzed.

Multilayer PCB's disturbs Signal Integrity. Eye diagram analysis is very useful when characterizing a device for a specific digital protocol. If the eye is sufficiently open and data transitions don't encroach into a standardized mask, then we can assume that we have compliance to that standard. Hence eye patterns are generated to analyze the Signal Integrity issues when the data lines are referenced over the solid ground plane and EBG plane.

5.1 Eye diagram characterization

S-parameters of the structures discussed above are exported from the CST Microwave Studio, 3-D Electromagnetic Solver by Touchstone format. Broad-band models

are extracted from the simulated S-parameters [16] that are compatible with Advanced design System (ADS) tool.

Eye patterns are generated using ADS circuit simulator by launching a Time-domain Pseudo-Random Bit Sequence Voltage Source. A non return to zero (NRZ) 2^8-1 pattern of pseudorandom binary sequence (PRBS), is given as an input (Port 1). The sequence is coded for different data rates and the signal propagation properties are monitored at the output port (Port 2). The input of the PRBS is coded

Fig. 13. Eye diagram of Square type Mushroom EBG: (a) Data rate 2 Gbps; (b) Data rate 1 Gbps.

Fig. 14. Eye diagram of Circular type Mushroom EBG: (a) Data rate 2 Gbps; (b) Data rate 1 Gbps

with 0.5V, voltage swing and rise/fall time of 200ps.

The Two parameters, Maximum Eye Opening (MEO) and Maximum Eye Width (MEW) are used as metrics of the eye pattern quality. Signal to Noise ratio (SNR) and Eye jitter are also measured. Figs. 13 and 14 show the simulated eye diagram of the received signal at the victim line end for square and circular Mushroom EBG respectively. Eye patterns were also generated for a Solid Power/Ground plane of the same dimensions to keep as a reference in estimating the degradation of the signal quality.

The eye pattern parameters of the square and circular EBG are given in Table 4. Maximum Eye opening (MEO) which is the Eye height, Maximum Eye width (MEW), SNR and jitter margin of the two types of EBG are compared with the Solid Power/Ground plane. The degradation of MEO and MEW is 26% and 9% for square EBG respectively for a data rate of 2Gbps. The value of degradation is reduced to 0.6% and 2% for the data rate of 1Gbps. For circular EBG MEW is good compared with Reference plane for data rate of 2Gbps.

5.2 Rise time measurement

A short pulse is given into the traces using Agilent Signal generator 332050A and corresponding NEXT voltage (at port 2) and FEXT voltage (at port 4) levels are measured using Tektronix DPO 4104 Digital Phosphor Oscilloscope.

The measurement setup is shown in Fig. 15 An input square wave, with a rise time of 10 ns and pulse width of

Table 4. Characteristics of Square and Circular EBG Structures

Eye pattern parameters	Solid power/ground plane		With square EBG		With circular EBG	
	Data rate 2Gbps	Data rate 2Gbps	Data rate 2Gbps	Data rate 1Gbps	Data rate 2Gbps	Data rate 1Gbps
Eye height (Volts)	0.321	0.331	0.295	0.325	0.268	0.318
Eye width (nano seconds)	0.45	0.99	0.36	0.97	0.5	0.97

Fig. 15. Experimental Setup for Time Domain Analysis

(a)

(b)

Fig. 16. Peak Voltage levels of traces with and without square EBG: (a) NEXT; (b) FEXT

(a)

(b)

Fig. 17. Peak Voltage levels of traces with and without circular EBG: (a) NEXT; (b) FEXT

200ns with amplitude of 2.5V is given at port 2. The NEXT & FEXT voltage levels are measured with a 4-channel Digital Phosphor oscilloscope at port 1 & port 3. The peaks in the figures will give the values of crosstalk in the near end and far end.

The results of NEXT and FEXT voltage levels of Mushroom type Square EBG is compared with the structure without EBG and is given in Fig. 16.

The results of NEXT and FEXT voltage levels of traces with mushroom type Circular EBG is compared with the traces without EBG and is given in Fig. 17.

From the results it is observed that the peak voltage level value of NEXT is 0.244mV without EBG and it is reduced to 0.074mV when Square and Circular EBG are used. The peak voltage level of FEXT is -0.156mV without EBG and it is reduced to -0.0056mV for Square EBG and -0.006mV for Circular EBG.

5.3 Time Domain reflectometry (TDR)

For time domain analysis, Time Domain Reflectometry (TDR) is used [17]. The advantage of performing time-domain measurements is that, the effects of a discontinuities along interconnects on SI can be directly observed, and models of the parasitic elements can be developed for the switching time of interest [17]. The TDR for the PCB trace having Square mushroom EBG, Circular Mushroom EBG and trace without EBG are shown in Fig. 18. From this figure, the impedance of the trace gets increased to

Fig. 18. Impedance Vs Time for traces with different EBG structures

51.5Ω and it is near to designed value of 50Ω due to the parallel high impedance offered by the square mushroom EBG array and the impedance of the trace is 52Ω for the PCB trace with Circular EBG

6. Conclusion

A new method is proposed to reduce NEXT and FEXT level using EBG structures. A 4x4 array of square Mushroom EBG and 2x4 array of Circular mushroom EBG are designed to reduce the far end crosstalk. The performance of these structures is analyzed in time domain and in frequency domain. Designed structures are fabricated and the measurement agrees with the simulated results.

From the designed model, circular EBG structure performance is good compared to other structure in terms of impedance matching, crosstalk reduction, and the number of patches used is very less. The coupling level is reduced to a great extent and further studies have to be done on jitter analysis of these structures so that small PCBs with high density of traces can be fabricated.

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