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A Novel Design of Electromagnetic Bandgap Structure and its Effects on PI and SI

***Abstract**. Power/Ground plane structure is the best configuration of the modern plane power distribution system. But in the high speed circuit, the resonant modes of the P/G planes can be excited when the high speed signal changes the reference plane. Thus it brings the ground bounce noise (GBN) and simultaneous switching noises (SSN) problems. This paper presents a novel electromagnetic bandgap structure which can suppress the high frequency and ultra-high frequency GBN and SSN by using a special S shape slender to connect the EBG unit. But the structure has a certain effect on the signal transmission features, while the simulation results show that loading the EBG structure in partial is not only able to restrain the GBN and SSN effectively, but also able to achieve good propagation characteristics.*

*Streszczenie. W artykule analizowane są szumy typu GBN I SSN. Zaprezxentoewano nową elektrlomagnetyczną strukturę pasmową umożliwiająca tłumienie tych szumów przy wysokich częstotliwościach. (**Nowe możliwości projektowania elektromagnetycznej struktury pasmowej i ich wpływ na szumy oraz sygnał**)*

Keywords: Electromagnetic bandgap (EBG), ground bounce noise(GBN), simultaneously switching noises(SSN), high-speed digital circuits, power distribution system (PDS), Signal Integrity(SI).
Słowa kluczowe: elektromagnetyczna struktura pasmowa EBG, szumy przełączania tranzystora

Introduction

In the recent ten years, the number of integrated transistor gates in chip increased dramatically and the power consumed by the devices is raised too. At the same time, the supply voltage of the devices decreased. All these factors make the power distribution system become the bottleneck of high-speed circuit design [1]. The challenge is expected to increase in next decade, because the signal speed is becoming faster while the integration of the system level and transfer speed of data communication is becoming higher [2]. The PDS noise above gigahertz will be expected to be serious because the distributed and parasitic effects of the PDS become dominant at higher frequencies. The power integrity design will be more challenging because of the wider bandwidth of the noise energy on the PDS [1].

Although the operating frequency of the microprocessor is very high (1GHz or higher), the transistors can switch in multiple frequency. So the power supply voltage will fluctuate in some special frequency ranges. The power distribution noise may be divided into four sections as shown below [3].

- Ultra-high frequency noise, 10GHz to 100GHz
- High frequency noise, 100MHz to 1GHz
- Intermediate frequency noise, 1MHz to 10 MHz
- Low frequency noise,1 KHz to 100KHz

On the printed circuit board, the power distribution system is composed of the power module, power/ground plane and a variety of capacitances. They can response in different frequency range. The power module can respond to the frequency range from DC to about 1 KHz. The large electrolytic capacitors can provide current and maintain low impedance in the range 1 KHz to 1MHz. The high-frequency capacitors can maintain low impedance in the frequency range with 1 MHz to several hundreds MHz. The PCB power/ground structure plays an important role over 100MHz.

Different ways can be used to reduce PDN noise in corresponding frequency. The first choice is using shunt capacitors to keep the PDN impedance very low in a low frequency range [4], [5]. However, decoupling capacitors are band-limited for providing a low-impedance path between the power and ground planes because the decoupling capacitors will become inductive in reducing the PDN noise above the self-resonance frequency. Another way to mitigate the PDN noise propagation is using electromagnetic bandgap (EBG) structures [6]–[10]. In different papers study shows that EBG structure can be well used in the high speed circuit to mitigate the high frequency noise. The basic idea of an EBG PDN is creating a 2-D periodic structure on the whole or partial power and/or ground planes.

The pattern is built by periodic square patches that connect to their adjacent patches. It does not require an additional metal layer and vias for the coplanar EBG structure like the mushroom EBG structure, but the power plane is periodically etched by slots. The coplanar EBG structure behaves like a low-pass filter, the patch providing the equivalent capacitance and the metal line providing the equivalent inductance. For coplanar EBG structures, the bandwidth enhancement could be achieved by increasing the bridge inductance. The inductance can be increased by using an L-shaped [11] or meander bridge that has a longer length of the bridge [12]. Another idea for increasing the bridge inductance is replacing the bridge by a SMT lumped inductor [13], which will bring an additional production cost.

Prior to this work, most EBG structures have been developed for large-scale backplane or motherboard applications. Several researches focus on the EBG power plane design to either lower the stop-band center frequency or broaden the stopband bandwidth for more efficiently suppressing[7][8]. However, the power and on-chip clock are expected to increase to 14.3GHz for the next decade[14].The concept of cascading EBG structures with different stop-bands were proposed to achieve wider bandgap bandwidth [15], But there are some drawbacks. One is much more power/ground planes area are occupied to cascade different stop-band EBG. The other is the performance is degraded at the transition frequency range between the two stop-bands for the cascading design.

The novel S-shape line EBG structure proposed in this paper can successfully suppress SSN or GBN at high frequency and ultra-high frequency. On the other hand, this S-shape line EBG structure can realize a wide bandgap which a cascading EBG structure ever achieved. At the same time, locally loading the EBG structure not only suppresses the power noise, but also minimizes the effect of the EBG-patterned reference plane on the transmission characteristics of high-speed signals.

A novel EBG structure for suppressing the high frequency Noise in Power integrity

1) Analyse and Design of the EBG unit cell

The mechanism of the bandgap formation can be divided into two kinds. One is the Bragg scattering mechanism including dielectric substrate drilling structure and ground layer etching structure. The other one is the local resonance mechanism containing mushroom EBG structure and UC-EBG structure. Different from the Bragg scattering mechanism, with the resonance EBG structure, the resonance effect of the unit itself plays a significant role in the bandgap formation. Through special design, the EBG structure unit can be equivalent to the parallel LC circuit with desired resonance frequency. The electromagnetic wave would be prevented to be generated near the resonance frequency because the EBG unit has an infinite impedance at this frequency. The frequency ranges in which the electromagnetic wave can not propagate are considered as the stopband. The centre frequency and relative bandwidth can approximately be decided by the equivalent inductance and capacitance of the surface unit [16]:

$$\omega_0 = \frac{1}{\sqrt{LC}} \quad (1)$$

$$\text{BW} = \frac{\Delta\omega}{\omega_0} = \frac{1}{\eta}\sqrt{\frac{L}{C}} \quad (2)$$

where η is the wave impedance of free space. Various methods can be used to enlarge the unit equivalent inductance and capacitance to obtain a more compact EBG structure, which is seen from equation (1).

The designed S-shape EBG unit cell is shown in Fig.1. The unit cell is composed of a square patch and S-shape lines. The gaps between the conductor edges of two adjacent cells introduce equivalent capacitance C. And the narrow S line, which connects the two units, introduces equivalent inductance L. Thus it can be described using the equivalent LC circuit. The equivalent capacitance and inductance of the unit cell can easily be changed by altering the S-shape arm and the width of the slot.

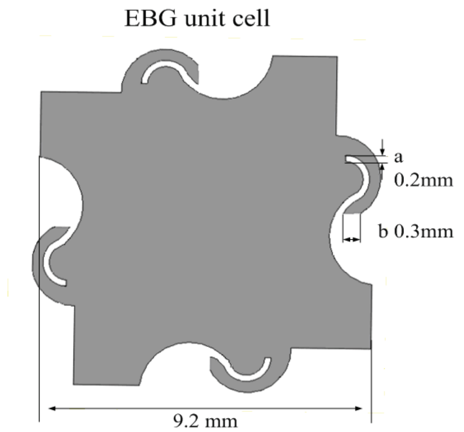


Fig. 1 EBG unit cell and the parameters.

The response of compact EBG is decided by three parameters, those are the start of bandgap, the bandwidth of stopband and the isolation that bandgap can achieve. The start and bandwidth of stopband depend on dispersion diagram of the compact EBG, while the isolation is obtained by extracting the S parameters of finite size of EBG. And the isolation improves with the increase of compact EBG unit cell's number.

The dispersion diagram is a propagation constant curve which is a function of frequency. The relationship between propagation constant and frequency determines the pass-band of compact EBG structure, and indicates that electromagnetic waves can be transmitted around this frequency. If the propagation constant and frequency have no connection, or the phase constant is purely imaginary, the wave will be attenuated or cannot be transmitted around this frequency, which results to form a stopband. We can get the bandgap of the compact EBG structure by using the dispersion diagram. In order to accurately analyze the surface wave bandgap of EBG structure, the infinite periodic unit cell model is used in this paper. With a electromagnetic simulation software (HFSS) based on finite element method and periodic boundaries [17], we can obtain the dispersion diagram as shown in Fig.2. Here Γ, X and M represent the symmetric points of Irreducible Brillouin Zone .The figure shows that there are three surface wave suppression bandgaps lying in 0.8GHz-1.6GHz, 4.5G-12.5G and 15.7G-24.6G.

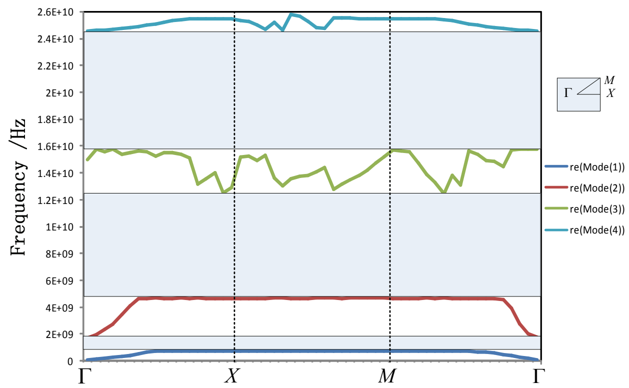


Fig. 2 Dispersion diagram for 2-D EBG structure.

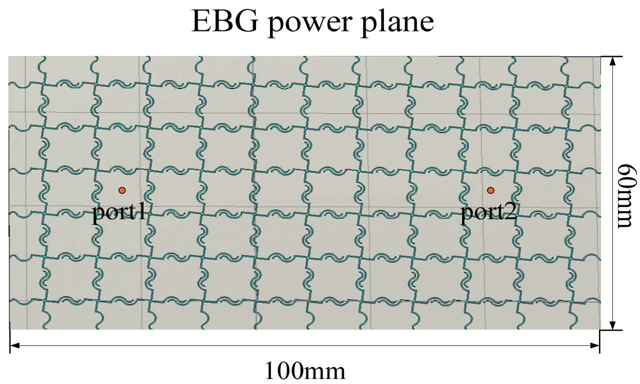


Fig. 3 Top view of the 11×6 EBG structure and the location of two ports.

2) Field distribution analysis of Power/Ground plane structure with EBG

To verify the characteristics of the novel EBG structure, a power distribution system with a power plane and a ground plane has been modelled with CST MW, which is a commercial electromagnetic simulator (shown in Fig.3). The power plane is etched to get the EBG structure. The ground plane is retained as a continuous metal plane to provide a return path for the high speed signal. According to signal integrity, it is crucial to keep the ground plane continuous. The layer between the power plane and the ground plane is a dielectric layer using the FR4 material with the dielectric constant 4.9 and the thickness of 1mm. The size of the plane is 100mm × 60mm. The EBG structure plane contains 11×6 EBG units to form an array as shown in Fig.4. To measure the bandgap of the EBG structure, two discrete ports, which locate in (42, 23) and (-23, 23) respectively, are placed in the EBG structure.

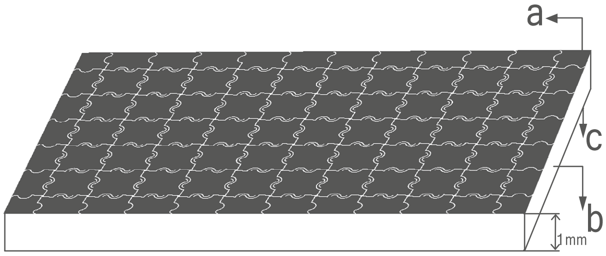


Fig.4 3D view of the power distribute system

Fig.5 shows the comparison of the electric field intensity between EBG board and reference board in magnitude. The left plots are the results of reference board, and the rights are the results of EBG board. They show that at the frequency points 8GHz、5GH and 400MHz, the designed EBG structure can provide a good isolation to prevent the noise excitation. The electric intensity distribution is bound to only one EBG unit cell.

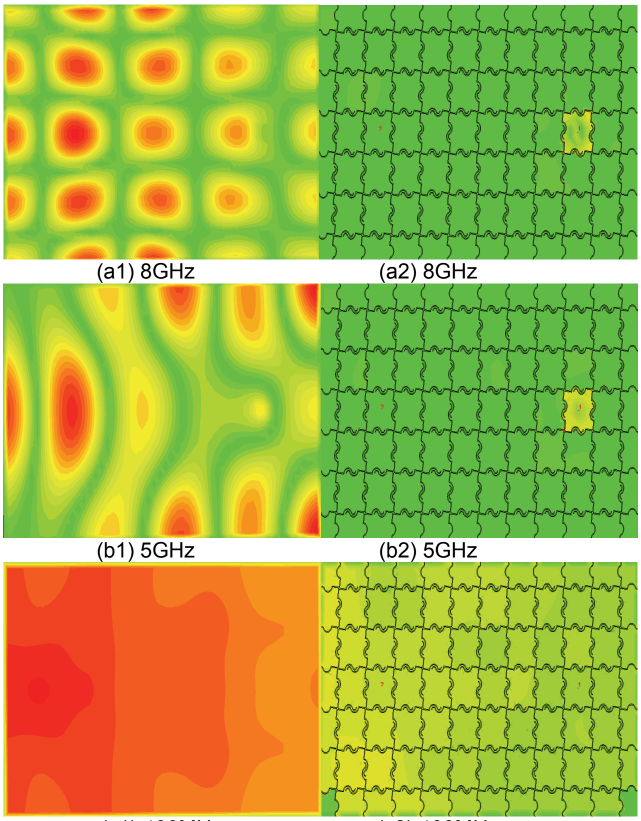


Fig.5 Comparison of the electronic field intensity between EBG board and reference board in magnitude. (a1) reference plane at 8GHz, (a2) EBG-patterned power plane at 8GHz; (b1) reference plane at 5GHz, (b2) EBG-patterned power plane at 5GHz; (c1) reference plane at 400MHz, (c2) EBG-patterned power plane at 400MHz.

3) Measurement resultS of Power/Ground plane structure with EBG

To verify the characteristics of the simulated structure, a two-layer PCB board was fabricated using laser etching technic as shown in Fig.6. The fabricated test board was fully EBG-patterned boards with S-shape line unit cells on the entire power plane. Two SMA connectors were assembled in the corresponding ports places. Vector network analyser was used to test the S_{21} parameter of the two ports.

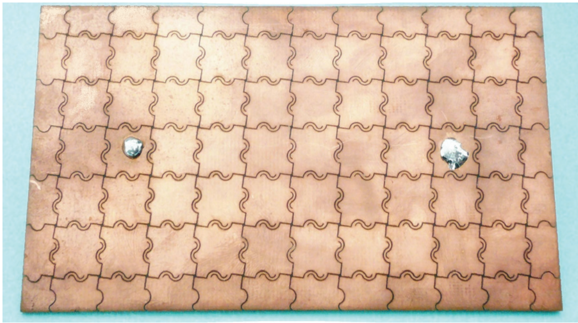


Fig. 6 Fabricated test board with EBG structure etched on the power plane.

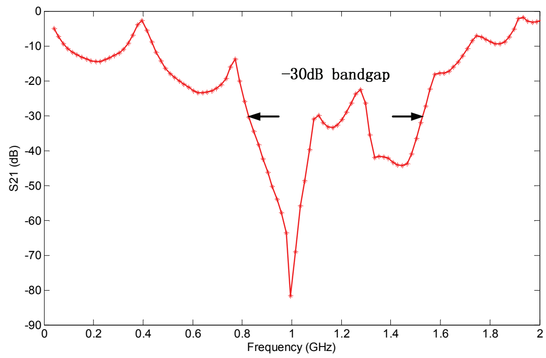


Fig.7 The measured $S_{21}$of the proposed structure from 400MHz to 2GHz

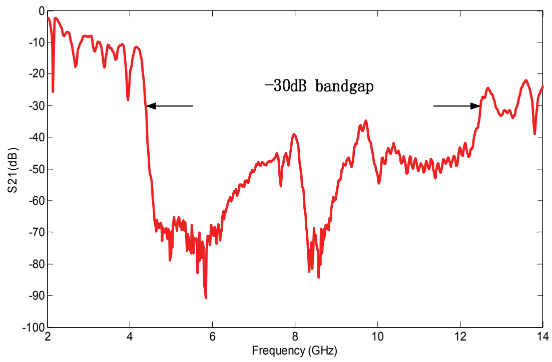


Fig.8 The measured S_{21} of the proposed structure from 2 to 14GHz

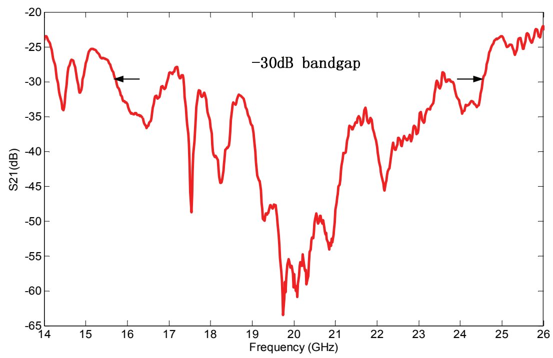


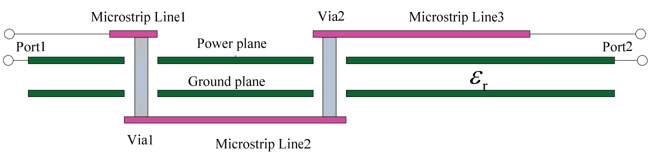
Fig.9 The measured S_{21} of the proposed structure from 14GHz to 26GHz

Fig.7, Fig.8 and Fig.9 are the S21 parameter curves of EBG plane at 400MHz-2GHz, 2GHz-14GHz and 14GHz-26GHz, respectively. The results show that the S-shaped EBG power/ground planes generate three stopbands in 0.82GHz-1.52GHz， 4.53G-12.49G and 15.73G-24.52G, with the bandgap depth below -30dB, which are the same as these in the dispersion diagram.

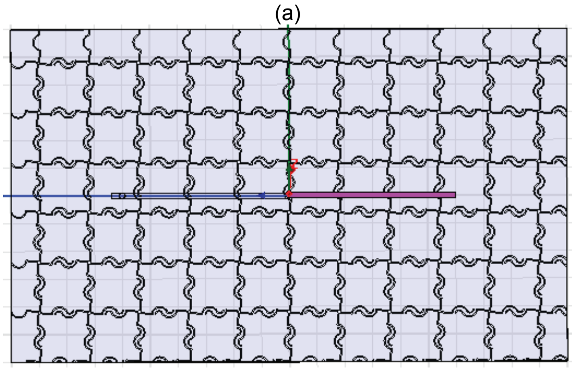
Effect on signal Transmission characteristics of the EBG structure

1) The simulation and analysis of S parameters

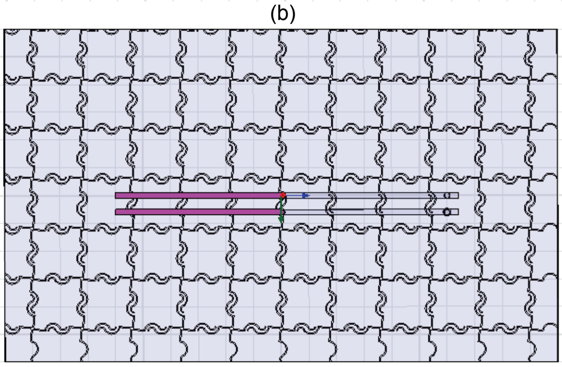
EBG structure has been successfully applied to suppress simultaneous switching noise, and the reduced magnitude and bandwidth of SSN have fulfilled very high requirements. However, because periodic high impedance surface of EBG structure destroys the integrity of signal return path, it may result in signal reflection and filtering, causing a serious distortion of high-speed signal. A signal trace of 62 mm passing from the first layer to the fourth layer and back to the first layer with two via transitions along the path is modelled in order to study the SI performance in presence of the EBG structure. The second and third layer is the S-shaped EBG power and solid ground planes, respectively. The considered structure is depicted in Fig.10, where the cross section is shown in Fig.10 (a), and the top views of single trace and differential pairs are shown in Fig.10 (b) and (c) respectively. The dimension of plane pairs is 100 mm ×60mm, line width of 1mm, line thickness of 0.1mm, two long microstrip lines of 30mm, short length of 2mm. Two vias are located at (0mm,0mm) and (0mm,30mm), respectively. The hole radius is 0.5mm and the pad radius is 0.75mm. The single line is terminated with 50 Ohm impedance while the differential pairs whose space is 2mm are ended with 100 Ohm impedance.



(a)



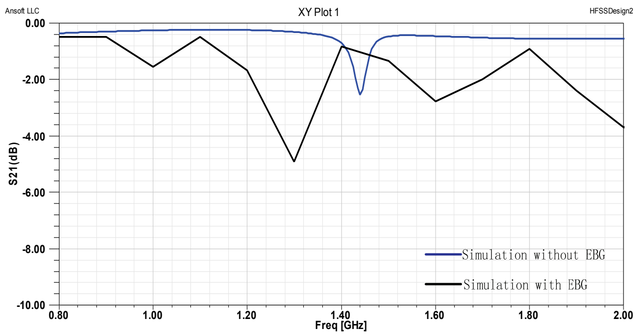
(b)



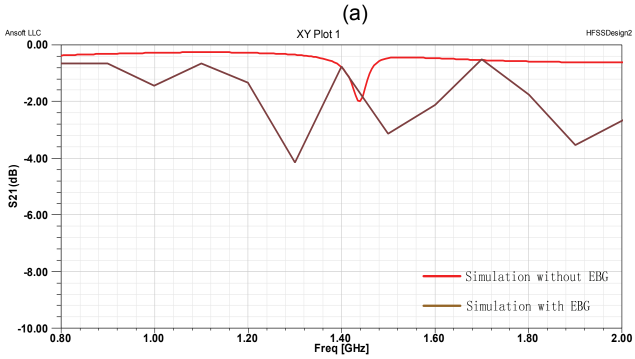
(c)

Fig.10 Cross section and top view of EBG plane with trace lines (a)cross section; (b)single trace; (c)differential pairs

Fig.11 compares the S21 parameters for the structure with EGB layer and continuous reference plane. The signal quality is influenced by the EBG structure, especially at 1.3GHz, a serious shift in the resonances is observed, S21 reducing nearly 4.6 dB with single line. S21 also reduces nearly 3.8 dB with differential pairs. Compared with single line, differential pairs coupled with each other besides the coupling with ground. The stronger coupling will be the major current return path. Although normally there is a little coupling between the differential pairs, only 10~20%, more coupling to the ground, when the local surface is discontinuous, the coupling between differential pairs will be the main loopback. The discontinuity reference plane has more serious effect on the single line compared with the differential pairs, but it still reduces the quality of differential signals.



(a)



(b)

Fig.11 S21 parameters for the structure with EGB layer and continuous reference plane. (a) singl trace; (b) differential pairs.

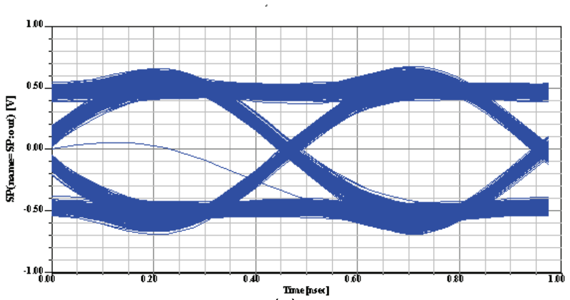
2) Analysis of eye diagram

EBG structure makes a very bad effect on transmission features due to two reasons in time domain. First, when the signal crosses an imperfect power plane, the impedance discontinuities will cause signal reflection back and forth between units, resulting in the generation of ringing noise. Another reason is that EBG structure will filter the high frequency components of signal, increasing the propagation delay and leading to signal waveform distortion.

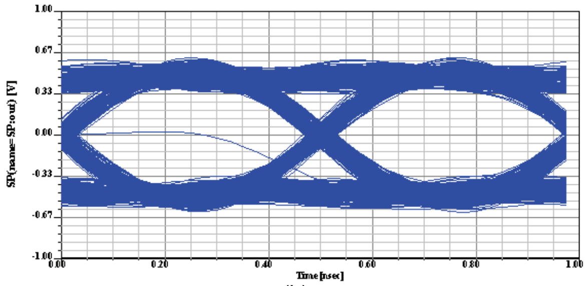
In this paper, the electromagnetic simulation software Ansoft Designer is used to simulate eye diagrams. The eye patterns at the output port of the transmission line are computed from the computation of the S-parameters in frequency domain. A pseudorandom (PRBS) bit sequence with the following parameters Tbit = 0.5 ns, tr = tf = 125ps, Vhigh =0.5 V, Vlow = -0.5 V is used as input. Two parameters, Maximum Eye Opening (MEO) and Maximum Eye Width (MEW) are used as metrics of the eye pattern quality.

For the reference board with continuous reference plane of single line, it results MEO=0.8 V and MEW=0.45ns (see Fig.12(a)) and for the board with EBG structure, MEO=0.76

V and MEW=0. 42ns (see Fig.12(b)). MEO and MEW become small, hinting that EBG structure will cause a certain degree of damage to the signal integrity.

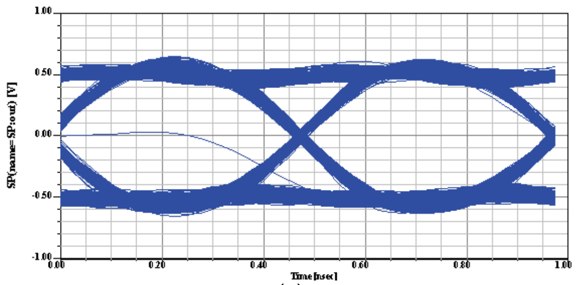


(a)

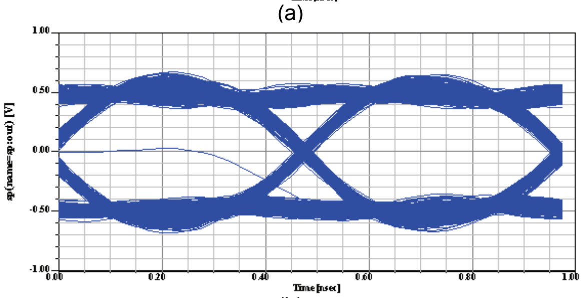


(b)

Fig.12 Eye diagram for single line. (a) Continuous reference plane; (b) EBG layer.



(a)



(b)

Fig.13 Eye diagram for differential pairs. (a) Continuous reference plane; (b) EBG layer

Fig.13(a) and (b) show the simulated eye patterns of differential pairs for the reference board and the considered EBG board, respectively. It is seen that for the reference board MEO=0.89V and MEW=0.47 ns, and for the EBG board MEO=0.8V and MEW=0.46ns. In contrast with the MEO and MEW for reference board of differential pairs, the MEO and MEW for the EBG board degradate about 10% and 2% respectively. Compared with the reference board of single line, the EBG board of differential pairs has no severe degradation of the signal quality. So contrasted with a single signal, differential signal can improve the quality of signal transmission to a certain extent. Of course, the SI performance will be better if the signal trace is shorter or the data transmission rate is slower than 2 Gbps.

The method for improving signal propagation properties

EBG structure has been widely used in power/ground plane because of the successful suppression of SSN, however, the application of EBG structure also bring some serious distortion to high-speed signal. Signal transmission alone a single line is greatly attenuated while it is improved by differential pairs. But the differential signal increases circuit design cost and board layout space, against large circuit design. Therefore, to improve the signal transmission properties, the transmission principles of the signal in EBG structure must be understood first. Signal on the EBG structure gets worse mainly because of the periodic high-impedance plane which demolishes the signal complete return path, resulting in periodic impedance changes, causing the signal disturbance. Therefore, in order to improve signal quality, avoiding problems caused by signal integrity, we should be looking for complete return path for signal as far as possible, that is to say, reducing the discontinuous area passed through by the signal. The methods can be accepted on the premise that the band gap range of EBG structure cannot be destroyed and thus they do not affect its inhibition to SSN. Partial EBG structure can perfectly solve this problem.

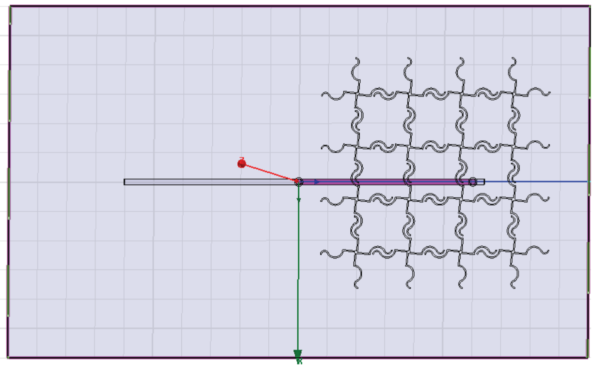


Fig.14 Top view of 3×3 EBG plane with signal line

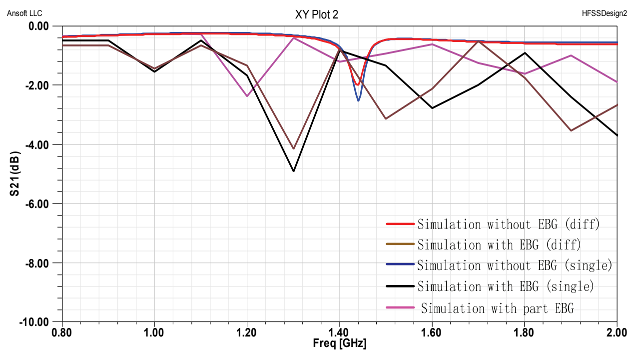


Fig.15 S parameters of signal trace with partial EBG.

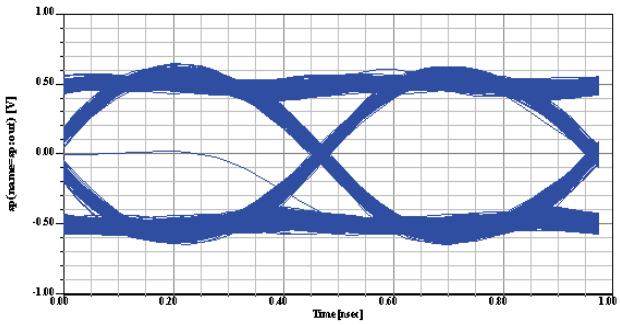


Fig.16 Eye diagram for single line with 3×3 EBG plane

Fig.14 shows a EBG plane with 3×3 unit cells, a signal propagating on a microstrip line designed as 50 Ohm with respect to the part EBG plane through a via down to the bottom layer and back to the top layer again. A through hole is amid the EBG structure and the signal propagation features are shown in Fig.15. It can be seen the signal quality is greatly improved if compared with the global EBG structure as shown in Fig.16. We can get more intuitive results from the eye diagram. For the board with part EBG structure, MEO=0.9V and MEW=0.47 ns (see Fig.16). The signal quality is better than the quality under the reference board of differential pairs. So partly loading EBG structure not only makes the signal quality improved, but also optimized in a specific frequency band. This may be caused by some sort of compensation or cancellation which can reduce the propagation loss between the discontinuity induced by partly loading the EBG structure and vias in frequency range from 0.8GHz to 2GHz. The other reason is that most of microstrip lies in continuous plane, the signal having complete return path, increasing S21 and improving the signal quality.

Conclusions

In this paper, a novel S-shape line EBG structure is proposed. The unit cell is composed of a metal patch and S-shape line. Compared with the existing structure，this novel structure does a little splitting on the power plane by using the S shape line to connect the units, thus makes the components layout convenient and the structure more compact. At the same time, this structure can be processed by laser etching technique at a low cost. The simulation and measurement results show that EBG-patterned plane can sufficiently suppresses the propagation of SSN and GBN with the high frequency from 0.8GHz to 1.6GHz and ultra-high frequency from 4.5GHz to 12.5GHz and 15.7GHz to 24.6GHz. Meanwhile, Partial EBG structure not only effectively restrains the power noise, but also minimizes the effect of the EBG-patterned reference plane on high-speed signals.

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