Modeling of Transmission Lines with Textured Ground Planes and Investigation of Data Transmission by Generating Eye Diagrams

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Abstract : In this paper, data transmission in transmission lines containing textured ground planes in the power distribution network is investigated. A lumped element model is developed to generate eye diagrams and circuit simulations are compared with measurements.

I. Introduction

Textured ground planes with Electromagnetic Bandgap (EBG) properties were first introduced to improve low-profile antenna design by providing a high impedance surface and blocking the propagating surface currents in certain frequency bands [1]. Recently, it has been proposed that this type of EBG structure to be employed in power distribution network (PDN) of high-speed digital and mixed-signal circuits in order to provide port isolation and global suppression of power/ground noise [2-5]. This type of noise, which is caused by the excitation of parallel-plate waveguide modes, appears as distributed voltage fluctuations on power/ground planes. Variations of reference voltage levels can alter the effective input thresholds in digital circuits, thus timing jitters and even false switching may occur. As clock frequencies and switching speeds increase and device supply voltages decrease, power/ground noise becomes more significant. Therefore, investigation of novel methods for suppression of this type of noise, especially employing the EBG structures, has gained much attention recently. In this endeavour, various EBG topologies, modeling schemes and characterization techniques are being studied [2-9]. Commonly, for characterization of EBG structures, the bandgaps and propagating modes are identified from the dispersion diagrams and the scattering parameter plots. However, in application of the EBG structures in PDNs, observation of time domain signature of reflected and transmitted signals and data streams is also required. Consequently, in order to monitor data transmission in the lines containing the EBG ground planes, not only the transient response but also the eye diagrams should be inspected to check for conformation with the signaling protocol of the intended application [6]. This verification can be done by conducting standard eye-diagram measurements or simulations of representative circuit models. Nevertheless, equivalent circuits, which allow integration of signal lines with the EBG ground planes, are still needed required to accurately characterize circuits utilizing this novel power distribution network. These models should capture the interaction between the EBG ground plane and signal lines, in a similar manner that the coupling between interconnects and conventional PDNs has been incorporated and reported in literature [10-11].

In the present paper, a circuit model for a transmission line with an EBG ground plane is introduced. The circuit model for the EBG structure is developed based on using LC components and considering each patch as a parallel-plate transmission line. This modeling strategy allows including two important features to the individual LC stages representing the EBG surface: coupling to the signal line, and transverse loading of adjacent patches in the EBG structure. The circuit model parameters are calculated by using closed-form relations and applying the physical dimensions of the structure-under-test. The proposed model is employed to generate the scattering-parameter graphs and eye diagrams, which are compared with full-wave simulations and measurements to ensure validation of the results in both frequency and time domains.

II. Modeling

Geometry: The EBG structure employed as the ground plane in the PDN is presented in Figure 1(a). The top metal layer has a checkered board layout with square patches of 9.6mm×9.6mm area, which are separated by 0.4mm wide gaps. The dielectric substrate used for the EBG structure is a double-sided 3.175mm thick Rogers RT/Duroid 5870 with $\varepsilon_r = 2.33$. Each patch on the top surface is connected to the bottom solid conductor surface by metalized via holes located at the center of the patch. This textured ground plane was fabricated and utilized in the stripline-like structure, shown in Figure 1(b). The line width is 2mm and the dielectric layers above the EBG surface are each 1.54mm thick FR4 laminates.

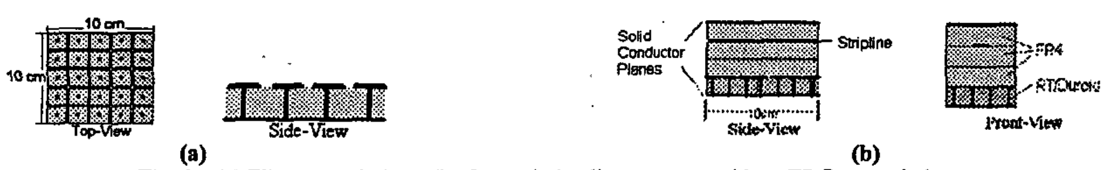


Fig. 1 – (a) EBG ground plane. (b) Transmission line structure with an EBG ground plane.

Circuit Model: The line and the patches in the textured ground plane are modeled each with LC sections, that are joined together by capacitive components. The gap between adjacent EBG patches is modeled with a capacitor and the via, connecting each patch to the bottom ground plane is represented by an inductor. Figure 2(a) shows the circuit model of a section along the patch, while Figures 2(b) and 2(c) depict the altered sections representing the via and the gap, respectively. It should be mentioned that in order to model the coupling to the upper ground plane and the EBG structure correctly, the pair of capacitors in the stripline LC model section had been each divided into two pairs. The outer pair of the capacitors connected to the ground (labeled $2/6C_l$) represents the coupling of the stripline to the upper ground plane, while the second pair connected to the EBG's LC model (labeled $1/6C_l$) includes the coupling of the stripline to the EBG structure. The coefficients applied to the capacitances are calculated based on the offset spacing of the line from the upper ground plane and the EBG structure. In order to incorporate the 2D nature of the EBG surface in the model, a transverse loading is introduced in the LC sections as proposed in [12]. The transverse load in the present circuit represents the effect of the adjacent patches that are modeled with successive LC sections, as shown in Figure 2(d). Subsequent patches at further transverse distances are not modeled, since their effects are found to be negligible from circuit simulations.

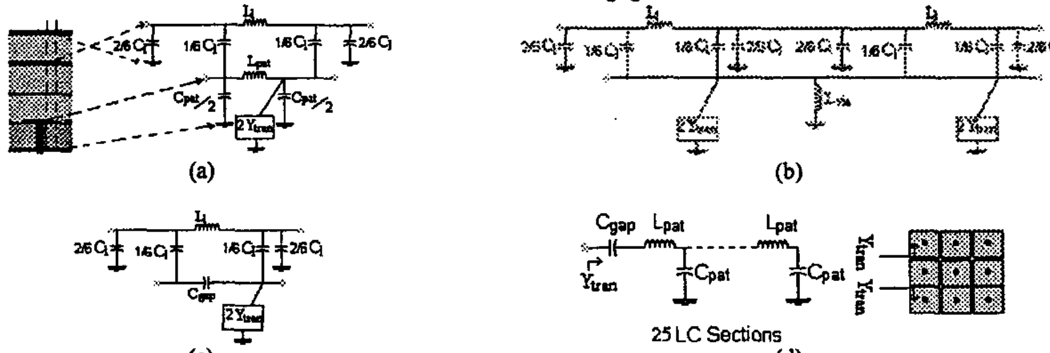


Fig. 2 – Equivalent circuit for a transmission line with an EBG ground plane: (a) Patch section, (b) via sections, (c) gap section, and (d) the equivalent circuit representing the transverse loading.

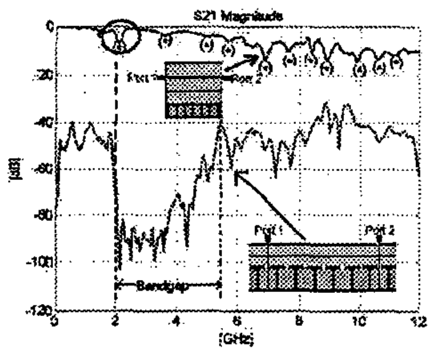


Fig. 3 – S_{21} measurements for a parallel-plate structure with an EBG surface and for the signal line shown in Figure 1(b).

The values for all LC components in Figure 2 are calculated using the formulas shown in Table 1. In order to determine the number of stages required for simulation of the 10cm line, the maximum frequency of interest in the spectrum of the test signal must be determined. The spectrum of a digital clock has two major corner frequencies at $f_1=1/(\pi T)$ and $f_2=1/(\pi t_r)$, where T is the clock period and t_r is the rise time, with $f_2 > f_1$ [13]. The maximum frequency that needs to be considered in a discretized transmission line circuit model is $f_{max} \approx f_2 = 1/(\pi t_r)$. The input signal used for measurement and simulation has a 10% to 90% risetime of 50 ps. Therefore, f_{max} is 6.37GHz and λ_{min} is 23.56mm. In order to have one section to represent the smallest feature size of the geometry, i.e. gap width, a section length of 400μm is needed. This number is well below the maximum tolerable section length to ensure accuracy in lumped element modeling of the transmission line (considering $\lambda_{min}/10 = 2.356$mm). With the chosen section length, a total of 25 sections are needed to model a single patch together with the adjacent patch spacing.

III. Measurement of the Bandgap

The first step in characterization of a textured ground plane employed in PDN is to verify the bandgap. For this purpose, the EBG surface was included in a parallel-plate structure, and the insertion loss between two vertical SMA connectors, as shown in the inset of Figure 3, was measured. Since the inner conductor of the SMA connectors were not soldered to the bottom ground plane, the magnitude of S_{21} was rather low. In order to see the effect of EBG on signal transmission, the structure depicted in Figure 1(b) was fabricated and the scattering parameters were measured. As shown in the inset of Figure 3, port 1 and port 2 in the structure are edge SMA connectors. It can be seen that loading of the textured ground plane on this transmission line is very small except for a glitch in S_{21} around 2 GHz, which corresponds to the beginning of the bandgap.

IV. Prediction of S-parameters from Circuit Simulations

Full-wave frequency domain simulations were performed to obtain the S-parameters of the structure shown in Figure 1(b). The magnitude of S_{21} obtained from full-wave and circuit simulations are presented in Figure 4. It is clearly shown that the circuit model accurately predicts the prominent EBG loading effect appearing at the beginning of the bandgap. Both full-wave and circuit simulations did not account for conductor and dielectric losses. Therefore, S_{21} does not exhibit the declining trend of S_{21} measurements shown in Figure 3. However, occurrence of the glitches in the measured S_{21} signature (as marked with * in Figures 3 and 4) are predicted with an excellent accuracy from circuit simulations.

Structure	Equations	Model Parameter Values
Patch – ε' is real part of electric permittivity, w is patch width, and d is the patch to ground plane distance [14].	$C=\frac{\varepsilon' w}{d},\ L=\frac{\mu d}{w}$	C_{pat} = 24.96fF, L_{pat} = 166.26pH (Section Length = 400μm)
Signal Line – c is the speed of light in free space [14]. (Z_o = 49.33Ω is the line characteristic impedance)	$C=\frac{\sqrt{\varepsilon_r}}{cZ_o},\ L=Z_o^2 C$	L_l = 131.557pH, C_l = 54.06fF (Section Length = 400μm)
Via– h_v is via height, and r_v is via radius [15].	$L_{via}=\frac{\mu_o}{2\pi}h_v\left(\ln\left(\frac{2h_v}{r_v}\right)+0.75\right)$	L_{via} = 1.718nH
Gap– w is patch width, ε_{r1} and ε_{r2} are substrate permittivities above EBG, ε_{r3} is EBG substrate permittivity, and g is gap width [1],[8].	$C_{gap}=\frac{w\varepsilon_o\left(1/2(\varepsilon_{r1}+\varepsilon_{r2})+\varepsilon_{r3}\right)}{\pi}\cosh^{-1}\left(\frac{2w}{g}\right)$	C_{gap} = 781.687fF

Table 1 – Equations

V. Evaluation of Data Transmission by Generating Eye Diagrams

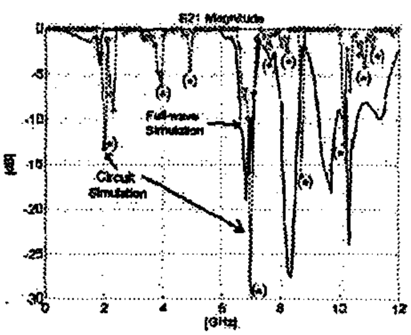
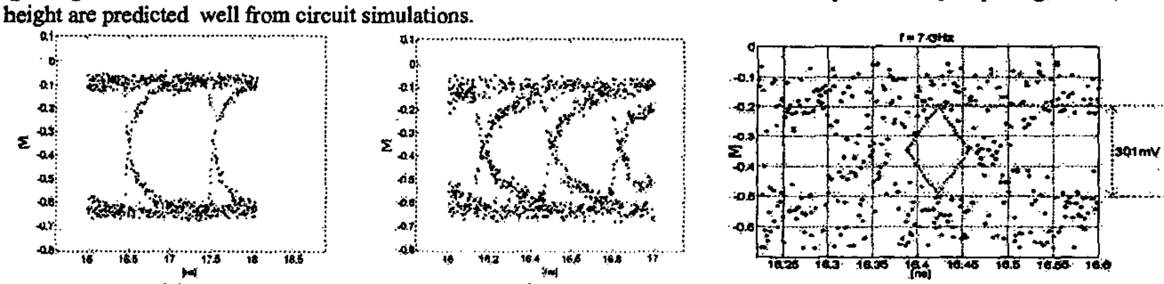


Fig. 4 – S_{21} simulation of circuit model.

To investigate data transmission, a pseudorandom binary sequence (PRBS) generator with magnitude of 600mV was employed to inject the input signal to the structure under test, as shown in Figure 1(b). The transmitted data was captured by a high-speed digitizing oscilloscope, while the input clock rate was varied from 100 MHz to 10 GHz. Measurement results for frequencies of 1 GHz, 3 GHz, and 7 GHz are presented in Figure 5. It can be seen that the opening of the eye diagrams can be easily recognized when the bit rate is below the bandgap frequency. However, as clock frequency increases beyond the bandgap, the eye opening becomes smaller and more rounded, representing a degradation of the signal transmission quality. Therefore, a dual structure, i.e. an offset stripline with solid conductor ground planes, was fabricated and tested to serve as a reference in evaluation of the eye diagrams generated at 1, 3, and 7 GHz clock frequencies. For the worst case scenario of 7 GHz clock frequency, the eye opening measured for the reference structure was 400 mV as opposed to the 301mV indicated in Figure 5(c). This demonstrates that the performance of a PDN with an EBG ground is comparable to a conventional PDN even at frequencies beyond the bandgap, while providing the additional features of global power/ground noise suppression and port isolation. Subsequently, the circuit model described in Section II was employed to obtain the eye diagram at the data rate of 100 MHz. In Figure 6, the eye diagram generated from circuit simulation is compared with measurement. The overshoot seen at the beginning of the eye is due to ignoring dielectric and conductor losses in the model. It can be observed that the shape of the eye opening, width, and height are predicted well from circuit simulations.



(a) (b) (c)

Fig. 5 Measured eye diagrams at clock frequencies of (a) 1 GHz, (b) 3 GHz, (c) 7 GHz.

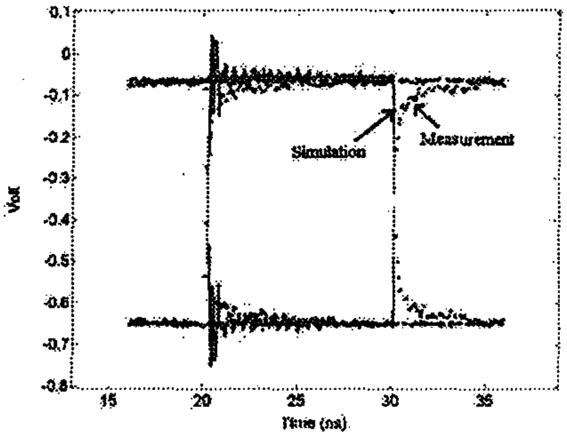


Fig. 6 – Eye diagram measuremed and simulated for clock frequency of 100 MHz.

VI. Conclusions

This paper investigates the application of textured ground planes, i.e. EBG structures, in the power distribution network (PDN) of high-speed digital circuits. This novel PDN have demonstrated to provide global suppression of power/ground noise and excellent port isolation. However, signal integrity issues associated with this method of PDN design have to be further studied. For this purpose, an equivalent circuit based on LC transmission line model is developed to represent the signal line with an EBG ground plane. Design formulas are presented herein to translate the physical dimensions of the geometry-under-test into lumped elements in the proposed equivalent circuits. Subsequently, the model is employed to generate the scattering parameters, transient response and eye diagrams for digital data transmission. In this paper, eye diagrams are monitored to quantify signal transmission when a textured ground plane is employed in the PDN, as the voltage fluctuations on the reference voltage planes contribute to voltage and timing jitters. To evaluate this characterization approach and to validate the proposed equivalent circuit, a number of test structures were fabricated and measured and an excellent correspondence between simulations and measurements was achieved. Finally, from the eye-diagram measurements, it was concluded that acceptable quality of data transmission can be achieved at high-speed clock rates while additional functionalities, such as noise suppression, can be obtained by utilizing textured ground planes.

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