1 Introduction

1.1 Motivations

This book is focused on a specific use of electromagnetic bandgap (EBG) structures: their function as common-mode (CM) filter in high-speed differential digital systems and/or hybrid mixed-signal circuits.

In order to appreciate the potential of these structures as signal filter, it is instructive to give a look to the historical development of the EBG structures at least since 1999 when they were proposed as high-impedance electromagnetic surfaces for band-stop filter [1,2].

The first application was related to flat metal sheets used in many antennas as reflectors or ground planes. These sheets support surface waves [3,4], that is, propagating electromagnetic waves that are bound to the interface between metal and free space. If the metal surface is smooth and flat, the surface wave will not couple to external propagating plane waves. However, they will radiate vertically if scattered by bends, discontinuities, or surface texture and this can generate, in case of multiple antenna placement, unwanted mutual coupling and interference.

By applying a special texture on a conducting surface, it is possible to alter its electromagnetic properties [5,6]. In the limit where the period of the surface texture is much smaller than the wavelength, the structure can be described using an effective medium model, and its qualities can be described by the surface impedance. A smooth conducting sheet has a low surface impedance; however, with a specially designed textured surface, the sheet can have a high surface impedance, thus inhibiting the flow of the currents over a selected frequency range.

The first example of EBG as high-impedance surface consisted in an array of metal protrusions on a flat metal sheet. They are arranged in a two-dimensional lattice and can be visualized as mushrooms protruding from the surface [7–11]. The surface can be easily fabricated using standard printed circuit boards (PCB)

Electromagnetic Bandgap (EBG) Structures: Common Mode Filters for High-Speed Digital Systems,
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technology. The protrusion are formed as metal patches connected to the lower continuous conducting surfaces by plated through-hole vias.

If the protrusions are small compared to the operating wavelength, their electromagnetic behavior can be described by using the lumped circuit theory. The EBG structure behaves like a network of parallel resonant *LC* circuits, which act as a two-dimensional electric filter to block the flow of currents along the sheet. In the frequency range where the surface impedance is high, the tangential magnetic field is small, even with a large electric field along the surface.

The mushroom-type EBG configuration has inspired the PCB designers to use this structure for suppressing noise in power planes [12]. An ideal power delivery network (PDN) is assumed to supply clean power to integrated circuits. However, electromagnetic noise in power/ground-reference planes can cause fluctuation or disturbance in the power supply voltage, which, in turn, leads to false switching, jitter, and malfunctioning in analog or digital circuits. Modern digital electronic circuits have increased the clock frequency and pulse edge rate, and has contributed to the decreased of the power supply voltage and noise margin. This power/ground-reference noise creates significant challenges for electromagnetic compatibility and signal/power integrity engineers. Simultaneous switching noise has become one of the major concerns [13,14] in high-speed PCB design.

This type of disturbance has been discussed extensively over the last decade [15–21] and different approaches have been proposed. Most prominent of these involve the use of discrete decoupling capacitors and embedded capacitances [22,23]. However, this approach fails when operated at high frequencies due to the inherent inductance of discrete capacitors and especially the inductance associated with connecting the capacitors to the power/ground-reference planes. Embedded capacitance is usually two very closely spaced planes (often with a higher than normal dielectric constant); it is an expensive solution and reliability considerations limit its practical use. Mushroom EBGs have proven effective for noise suppression at frequencies above 1 GHz and can be effective when discrete capacitors and/or embedded capacitance cannot be effective. When the mushroom-type configuration is implemented in PCB, it uses three layers where the EBG pattern layer with specially designed vias is inserted between the power plane and a ground-reference plane, as shown in Figure 1.1. This configuration makes the fabrication more expensive since extra PCB layers are used for the filter.

The natural evolution of the mushroom-type EBG applied to PDN in printed circuit boards have been the planar EBG structures used either for switching noise mitigation or in mixed-signal boards [24–33]. These structures consist of a power distribution system of only two layers, instead of three of the mushroom type, with one of the layers patterned in a periodic fashion, effectively creating a frequency band-stop filter. These structures, in contrast

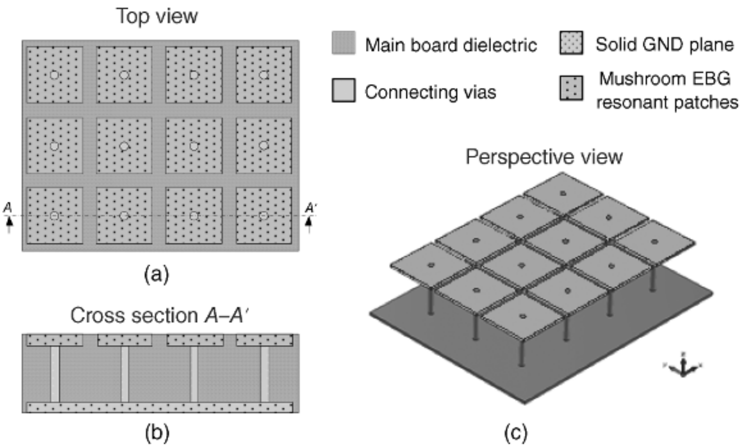


Figure 1.1 Mushroom EBG configuration. (a) Top view. (b) Cross-sectional view. (c) Perspective view.

to the previously described mushroom filters, do not have vias or require the third layer. These features make such structures very attractive for PCB applications from the manufacturing and cost perspectives.

Their basic structure is illustrated in Figure 1.2.

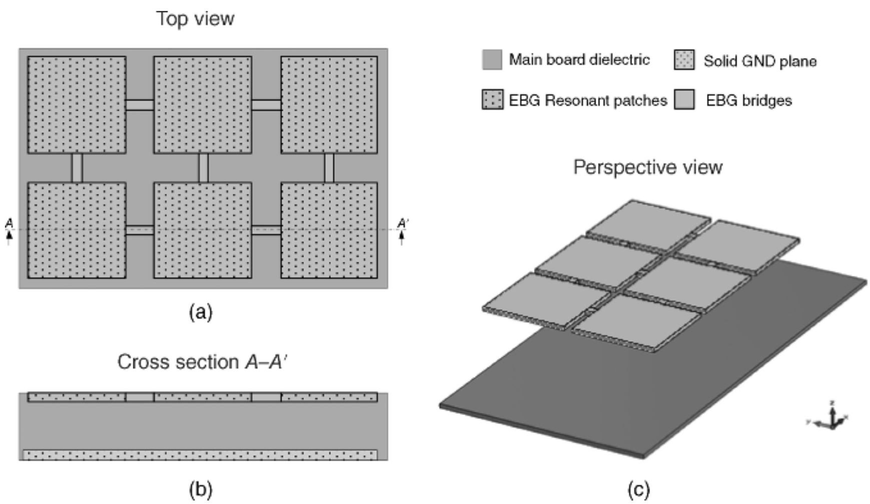


Figure 1.2 Planar EBG configuration. (a) Top view. (b) Cross-sectional view. (c) Perspective view.

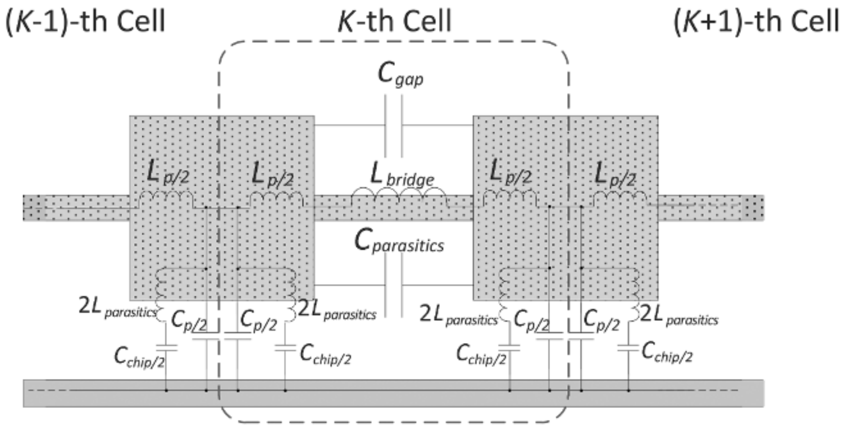


Figure 1.3 Qualitative equivalent circuit of a unit cell of a planar EBG structure.

In this basic structure, the solid layer can be used for one voltage level and the EBG patterned one for a second voltage level (often ground-reference). Between these two layers, there is a uniform substrate material whose nature (organic, ceramic, lossy, etc.) depends on the application of the board and the performances of the filter. For one-dimensional wave propagation, the unit cell of this planar EBG structure can be modeled with the basic equivalent circuit shown in Figure 1.3 [34–38].

The left part of the figure describes the propagation characteristics between the EBG patch and the continuous power plane represented by the equivalent patch inductance L_p and capacitance C_p. The second part of the figure characterizes the bridge effects between two adjacent unit cells. The gap between two patches generates a fringing electric filed associated with the equivalent capacitance C_b and the bridge's inductance L_{bridge}. A repetition of these cells can be conceptually viewed as an electric filter of parallel *LC* resonators.

The basic structure of the mushroom-like EBG structure has evolved to the concept of the ground-reference surface perturbation lattice (GSPL) geometry [39–44]. This structure is similar to the EBG filter but with multiple vias, and its design or use is typically appropriate when there is a need to enhance the bandwidth of the bandgap for power delivery noise suppression [45–49]. By using multiple shorting vias and optimizing their arrangement, the GSPL structure presents a wider bandwidth bandgap than that of the mushroom-like structure. In the GSPL, the mechanism of the bandwidth enhancement is based on the optimization of the vias locations. A one-dimensional equivalent circuit model, conceptually similar to that illustrated in Figure 1.3, can be used to predict the stopband. Test structures are manufactured on FR4 substrate to

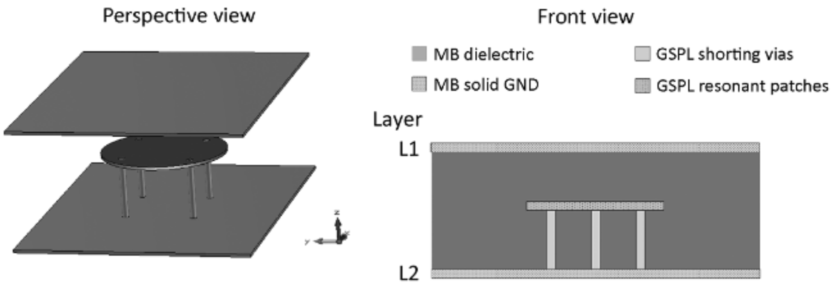


Figure 1.4 GSPL with four vias. MB = mother board.

compare the measured results and the numerical ones. Figure 1.4 shows a GSPL with four vias.

After the previous brief review of the main frequency-selective structures similar to or derived from the EBGs, it is possible to move toward the description of a more specific application: their use as signals filter in digital systems.

Where data rates get into the high hundreds of megabits (Mb/s) or gigabits (Gb/s), signal integrity (SI) concerns will usually require that differential signaling is used in order to ensure the required signal quality. Dielectric loss for long traces, reflections from connectors and vias, and even surface roughness will reduce signal quality at the end of long traces at very high data rates.

Differential signaling is also more immune to external noise corrupting the intentional signals. The basic intention for differential signals is for two equal and opposite currents (and voltages) to exist on the pair of traces, and the ground-reference plane plays no role in the intentional signal current. In reality, this is true only when there are only two signal conductors in free space, with no other metal nearby. This perfect condition never occurs in typical printed circuit boards [50]; therefore, there is always some RF currents on the ground-reference plane in real-world PCBs.

The presence of common-mode noise in the differential signal is one of the main causes of electromagnetic interference (EMI) problems in chip packages and printed circuit boards, especially in the gigahertz range of state-of-the-art high-speed digital systems. The common-mode signal can propagate outside the shielded enclosure through connectors and cables and cause unwanted external radiation.

The previously introduced EBG structures are primarily used for noise mitigation in PCBs and packages, thus enhancing the power integrity performance of the power delivery network [51,52]. The regular planar EBG is investigated in Ref. [53], studying the effects of the patterned plane on both common-mode and differential-mode signal propagation along a differential

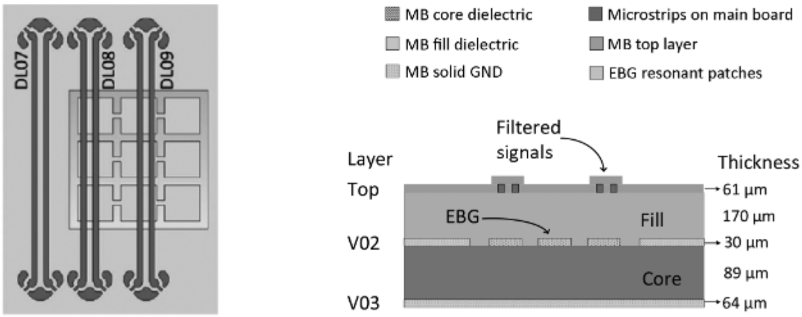


Figure 1.5 Basic onboard EBG CM filter structure for common-mode filtering: external layers layout.

microstrip line. These principles are applied for filtering the common-mode noise (due to some imbalance) in a differential signal [54–65].

The electromagnetic properties and the layout technique regulating the EBG common-mode filter behavior will be discussed in several parts and under different perspectives across the book. These EBG filters can be placed near *I*/*O* connectors on PCBs to reduce the amount of common-mode current that is coupled onto the cables or near ICs to suppress the common-mode noise near its source.

The most simple EBG-based CM filter is laid out on the PCB outermost stack-up layer (the so-called top and bottom layers) as in Figure 1.5 and is sometime referenced as an onboard EBG CM filter. The figure shows the real layout of a manufactured board that was employed for investigating the cross talk among adjacent differential pairs routed on the same EBG filter [66,67].

These onboard EBG CM filters can also be laid out on the internal layers of the stack-up, as shown in Figure 1.6. The stripline filter consists of two patterned layers above and below the differential traces: In this way the return current flows on both the planes above and underneath the traces.A possible variation to the classic EBG structure is the removing of the bridges connecting the patches. This new configuration (Figure 1.7) in general provides deeper notches (but less bandwidth of the bandgap filter) than the regular EBG structure for filtering the common-mode signal.

These EBG filter configurations are designed to attenuate the common-mode component of the signal, as shown by the common-mode mixed-mode scattering parameter S_{cc21} in Figure 1.8a, without affecting the transmission of the differential mode and thus without spoiling signal integrity of the output eye diagram as shown in Figure 1.8b.

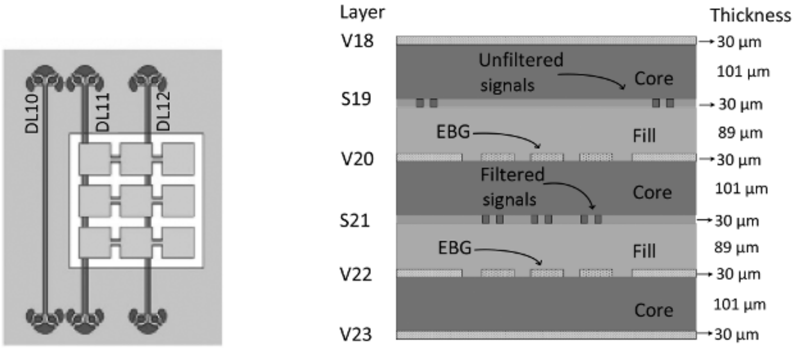


Figure 1.6 Basic onboard EBG CM filter structure for common-mode filtering: internal layers layout.

A different layout strategy was adopted in Refs [68–73] to provide more flexibility in the filter design. The EBG filter is eliminated from the PCB stack-up, and it is modified to be a surface-mount component installed on top of a PCB. In the literature, this configuration is referred to as a *removable* EBG CM filter. Also, with this configuration, the key design concepts such as the use of standard multilayer laminate technology, the straightforward design procedure, and the reduced costs that make the EBG filter attractive are still valid. Moreover, the electromagnetic behavior of the filter remains unchanged,

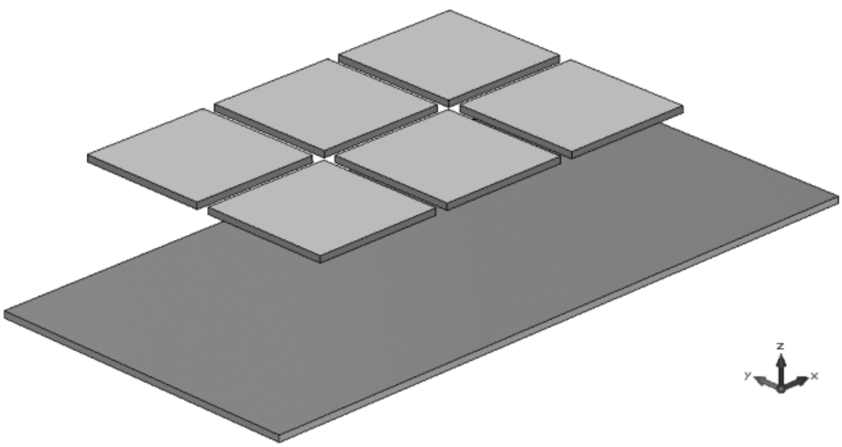
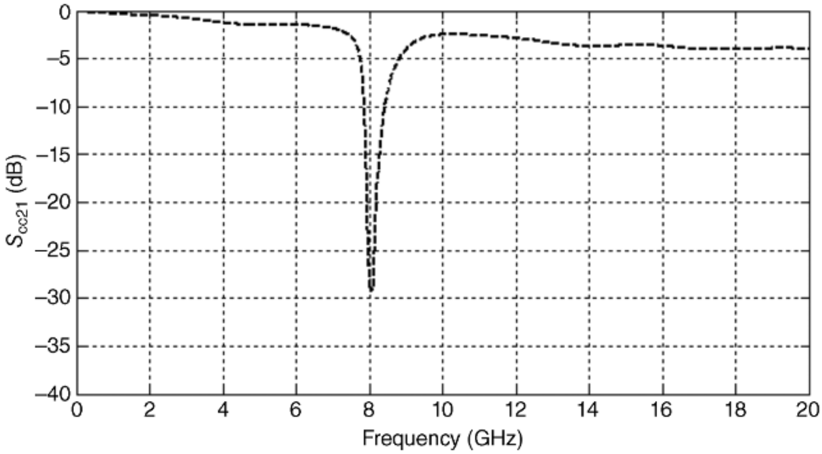
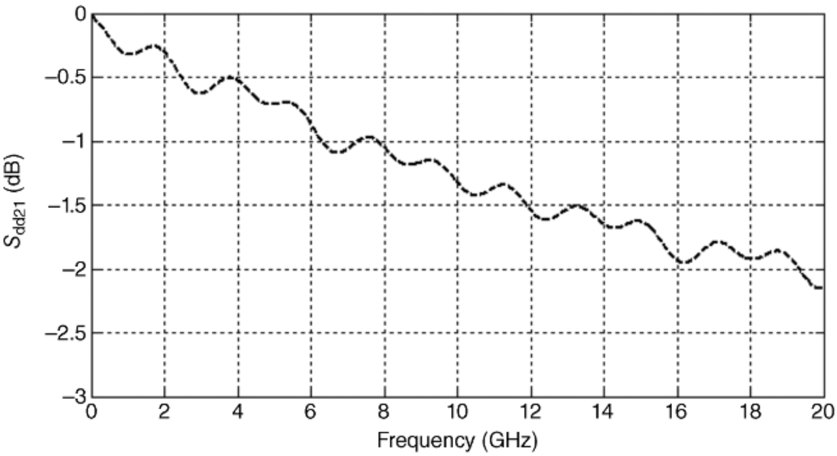


Figure 1.7 Modified onboard EBG CM filter structure for common-mode filtering.



(a)



(b)

Figure 1.8 Mixed-mode scattering parameters for EBG CM filters. (a) S_{cc21}. (b) S_{dd21}.

with the common-mode return currents of the differential pair being responsible for the common mode to EBG cavity mode coupling. The PCB area used by the removable EBG CM filter can be minimized by employing techniques for its miniaturization; the simplest strategy is to utilize a high-permittivity material whose larger costs, with respect to the standard laminates (i.e., FR-4), remains limited to a millimeter-size multilayer PCB rather than the main PCB.

A qualitative example of removable EBG CM filter is given in Figure 1.9.

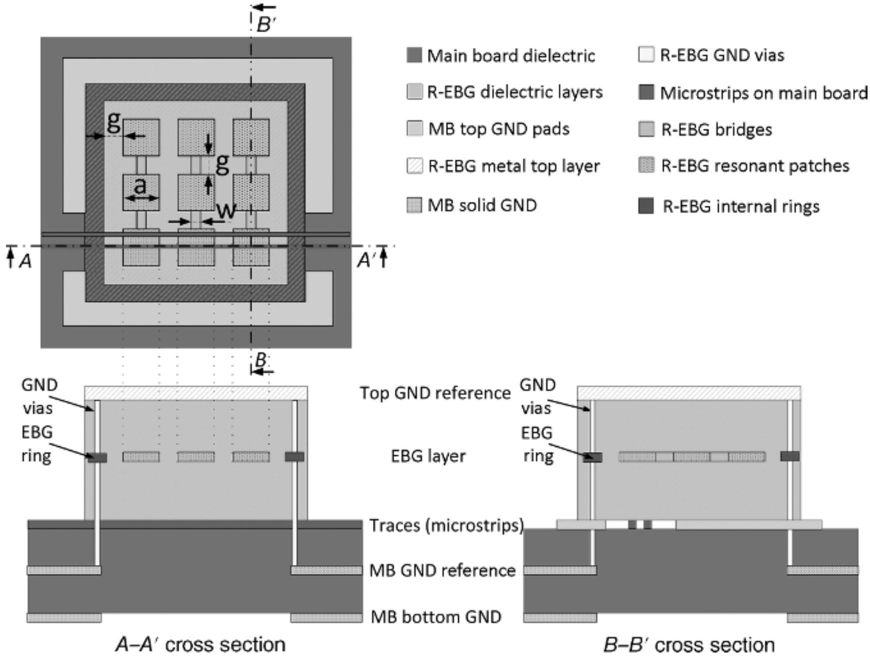


Figure 1.9 Basic removable EBG CM filter structure for common-mode filtering.

The filter is attached to the PCB by means of four corner pads for the current return corresponding to pads on the PCB.

The performances of such *removable* configuration are as good as the *onboard* counterpart. Figure 1.10 shows a S_{cc21} for this filter, very well centered

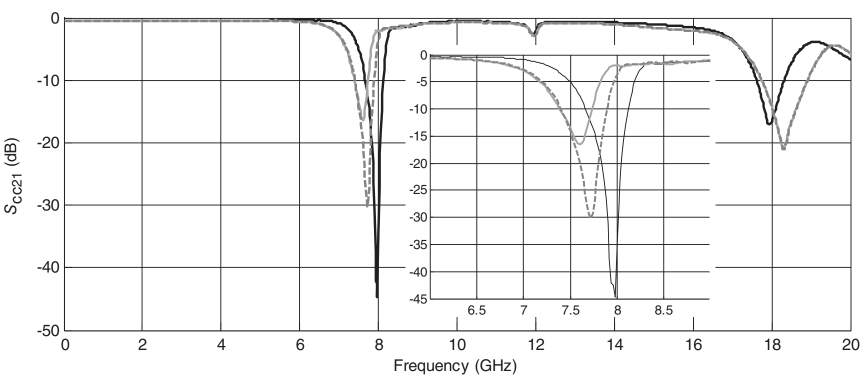


Figure 1.10 Mixed-mode scattering parameters S_{cc21} for a removable EBG CM filter.

on the design frequency (i.e., 8 GHz) and its sensitivity due to the variation of geometrical parameters, as will be discussed in this book.

In conclusion of this brief introduction to the topic of the implementation of the electromagnetic bandgap structures as CM filters for high-speed differential signals, it should be mentioned that the actual research trend is toward the miniaturization of these structures in order to minimize their dimensions without affecting the filtering performances [74].

The more recent scientific literature shows two different approaches to reach this goal: the use of material with high dielectric permittivity and the design of patterned structures using novel resonators with limited dimensions to excite the filter resonances.

The former approach has explored the use of ceramic dielectric such as the low-temperature co-fired ceramic (LTCC) [75,76] and it is suitable for the use of the removable filters because they allow a decoupling between the dielectric material of the main board and that of the component itself.

The latter is showing very promising miniaturization factors of around 10 times the standard EBG CM filters [77–79]. These resonators can be easily implemented on PCB or even on package substrate by designing an open stub with shorting via connecting to the reference plane. This configuration provides the shorting path of the common-mode return currents at gigahertz range and still maintains the isolation at DC level.

Finally, particularly significant to have a complete outlook of the EBG field of applications are Refs [80–83].

All the three-dimensional full-wave simulations have been performed by using the *CST Studio Suite 2015* by *Computer Simulation Technology* (CST) [84] and the *Advanced Design System* (ADS) environment by *Keysight Technology* [85] for the transient and frequency analysis of the equivalent circuit models.

1.2 Scope of the Book

The book aims at providing the basic principles of operation of the planar EBG structures as common-mode filters for high data rate digital systems. The following is a brief description of the chapterwise coverage of different topics.

This chapter introduces the topic of the book, offering a brief historical perspective of the introduction and use of the EBGs in the printed circuit board world and their evolution into CM filters.

Chapter 2 describes the fundamental mechanisms of planar EBGs looking into details of the mechanisms of resonances and the definition of the lower and higher boundaries of the bandgap as well as proposes the design criteria for these structures with particular emphasis on their impact on power integrity.

Chapter 3 is devoted to the study of the structures described in Chapter 2, but also looking at their impact on the integrity of signals flowing on single-ended and/or differential traces routed above or between EBG filters. This chapter shows the common-mode filter on a differential trace referenced to a patterned plane is equivalent to the response of a single-ended trace reference to the same plane. This finding will be the basis for the use of the EBGs as filters.

Chapter 4 introduces the concept of *onboard* EBG CM filter based on a simple patch resonant cavity. This approach permits a simple and detailed theoretical treatment that allows the reader to easily design their own EBG CM filter for their specific application. Some full-wave examples and simulation results are presented and compared to validate the design approach.

Chapter 5 contains few specific topics concerning the design and implementation of EBG CM filters:

- Techniques to enhance the bandwidth of the bandgap associated with the EBG such as multiple size of patches and bridges.
- Approaches to reduce the overall size of the EBG on the printed circuit board.

Chapter 6 is similar in structure to Chapter 4: It discusses the evolution of the *onboard* EBG CM filters in *removable* EBG CM filters. These removable filters allow designers to replace EBG filters on the board according to their needs without redesigning the overall board. This chapter presents different topologies of removable EBG CM filters, from the one with the traces kept on the main PCB to the second configuration with the differential pair routed on (or inside) the removable part. This chapter also contains details of the miniaturization techniques for the EBG CM filters and their external electromagnetic radiation.

Chapter 7 describes a number of measurements made to validate the operations of CM EBG filters as designed in previous chapters. The main content of this chapter is to provide information and details of the measurement setup and procedures to measure the signal integrity and EMC performances of these EBG structures. A detailed description of the measurement techniques and of the calibration and de-embedding strategies are included.

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