Miniaturized On-PCB RF Filter Design Based on Electromagnetic Bandgap Structure

Je Kyung Lee, Anuj Y. Modi, Tzung-I Lee, and Cheol-Su Kim
Amazon Lab126, Sunnyvale, CA 94089, USA
jekyulee@amazon.com

***Abstract*—This paper proposes a new Electromagnetic Band-Gap (EBG) Structure based filter design. This on-PCB filter imitates the functionality of a discrete low-pass filter without any of the associated Bill of Materials (BOM) costs. The methodology of constructing the EBG filter is explained in detail, making use of classical filter theory including tapering and multiple elements that enable tradeoffs between roll-off, rejection, and pass-band ripple. Furthermore, techniques such as multi-layer modulation and diagonal vias are utilized to reduce the physical footprint of the design. This addresses the limitation of prior designs which caused them to be inefficient due to their excessive area requirements and unmanageable pass-band ripple. Modeling and simulation was done using Computer Simulation Technology (CST), with the filter exhibiting a pass-band from 6-7 GHz and a stop-band from 8.45-22 GHz.**

I. Introduction

The increasing compactness of consumer electronics makes the task of maintaining the necessary isolation in desired Radio Frequency (RF) bands between various radios and antennas challenging. To address this concern, additional lumped component filters and shields need to be implemented to compartmentalize individual radios, leading to increased cost. Sub-wavelength structures, specifically the proposed EBG, have the potential to remedy the issues that come with both device size and complexity. Sub-wavelength structures are periodic structures with a periodicity smaller than the wavelength of the relevant band [1]. Owing to their periodic character, band-gaps emerge in these structures and suppress surface waves within the frequency range corresponding to the band-gap [1]–[4]. In this work, a novel miniaturized RF filter based on an EBG structure has been proposed and a three cell filter design has been reported. The sample filter utilizes three layers of multi layered board (MLB) having FR-4 as a substrate between the metal layers. To verify the effectiveness of the design, the filter has been simulated using a commercial EM fullwave solver (e.g. CST Microwave Studio) [5]. The simulated data suggests that the synthesized three cell RF filter meets the design criteria, thus elucidating its potential for various practical applications.

II. Design

The design of the proposed EBG filter is based on the mushroom-like structure which consists of a metal patch over a dielectric substrate with a ground plane [1]. There is a metal via that connects the center of each metal patch through the substrate to the ground plane. The original EBG is periodic in two dimensions, so the unit cell repeats itself in both directions in the plane of the substrate at every periodic width. The patch on top does not span the entire periodic width, so there is a gap between each of the metal patches in which only substrate and the ground plane resides below it. This gap between patches creates an equivalent series capacitance while the vias down to the ground plane create a shunt inductance.

The proposed EBG filter improves upon this base mushroom-like structure by combining multiple design techniques detailed in sub-sections below. The proposed EBG filter is a 1-D periodic, three unit-cell structure that uses three metal layers instead of the two layer structure [1]. It uses two vias on opposite corners of the structure to create an inductive ground loop that maximizes inductance along the width of the structure. Geometrical tapering is applied to the widths and lengths of the patches. The proposed EBG filter has a 50Ω microstrip line at the input and output of the structure, but can be easily modified to have microstrips of any impedance at the input and output without greatly affecting the filter performance. The top layer is then modulated to include different widths of microstrip to increase capacitance over the layer 2 patches as well as increase inductance in the gaps between patches. The overall area of the proposed EBG filter is 4 mm × 6 mm which is small enough to fit within the space that would be taken by a multi-stage lumped element filter (Figure 1).

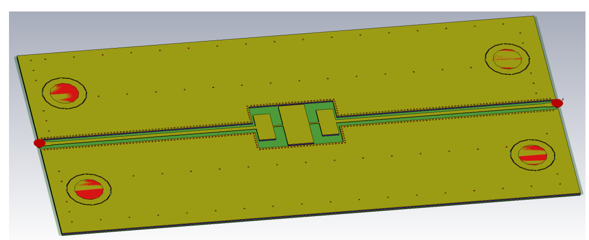

Fig. 1. Isometric view of the sample design and simulation setup of the EBG-based miniaturized filter

Fig. 2. Side view of the proposed filter to show three layer design with vias from layer two to three

A. Multi-Layer and Multi-Cell

In order to replace lumped element filters the EBG structure would require integration with an in-line transmission line so that the EBG filter could be placed in series. This realization spawned multiple multi-layer derivatives of the mushroom-like structure with a microstrip integrated on the top layer [4], and thus a multi-layer design was used. As in classical filter theory, the number of elements that a filter uses enables the designer to trade-off between pass-band ripple versus bandwidth and rejection of the stop-band.

B. Tapering

Tapering of capacitance and inductance values is achieved by tapering the physical width and length of the EBG unit-cells on either side of the center element. Tapering enables the designer to trade-off pass-band ripple and bandwidth versus the roll-off and rejection of the stop-band.

C. Multi-Layer Modulation

Other EBG-based filters [4] have a uniform width of microstrip line on the top layer that runs on top of the layer 2 patches. However, the proposed filter utilizes modulation of multiple layers to increase the effective capacitance and inductance that the filter can have within the same area. Thus, a smaller effective area can yield the necessary amount of capacitance and inductance of the filter, allowing for miniaturization of the structure.

D. Location of Vias

The ground loop created by the two vias from layer 2 to ground is the mechanism that creates effective inductance for the EBG filter. Thus, optimizing the placement of the vias gives the designer fine control over the amount of effective inductance the filter has (Figure 2). The location of the vias are also effectively tapered due to geometrical tapering of the layer 2 patches, so the effective inductance is tapered by the same coefficient as the parallel plate capacitance is tapered.

III. Simulation Results

The simulation setup of the proposed EBG uses the top three layers of an 8-layer board. The input and output of the EBG is a 50Ω microstrip that extends to the pads of a 3.5mm connector. Discrete ports are placed at the edge of the pad of the connector on either side of the EBG. The proposed filter features less than 3 dB insertion loss (without de-embedding of 50Ω microstrip lines) within the required 6 GHz to 7 GHz range for WiFi 6 (Figure 3).

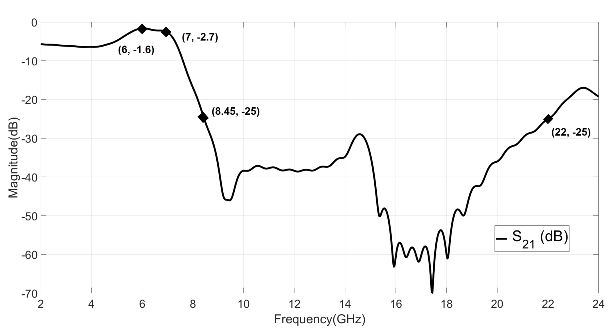

Fig. 3. S_{21}(dB) indicates that the filter meets the insertion loss requirement of less than 3 dB within the pass-band, while simultaneously achieving greater than 25 dB of attenuation in the stop-band.

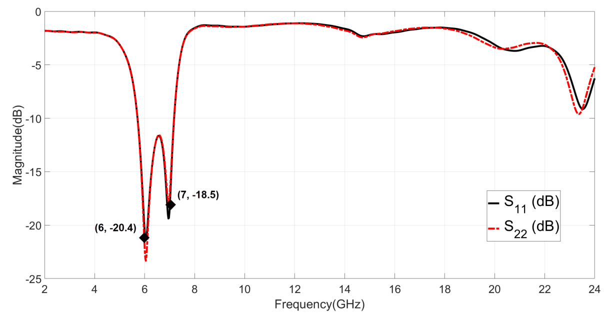

Fig. 4. The S_{11}(dB) and S_{22}(dB) evaluations of the proposed filter demonstrate a pass-band return loss of greater than 10 dB.

The proposed filter has a return loss of more than 10 dB throughout the same range, as displayed in Figure 4. The tapering applied to the physical dimensions of each cell of the filter helps achieve a flat pass-band response by eliminating ripples while maintaining a good rejection response in the stop-band frequency range. The filter provides more than 25 dB rejection in the stop-band from 8.45 GHz to 22 GHz, as illustrated in Figure 3.

IV. Conclusion

This paper has successfully proposed a novel EBG Structure based miniaturized RF filter. It has been extensively modeled and simulated in CST, showing a pass-band from 6 GHz - 7 GHz and stop-band from 8.45 GHz - 22 GHz; this is able to mimic the performance of a discrete low-pass filter without any added BOM cost. Additionally, techniques such as multi-layer modulation and vias at optimum locations were used to miniaturize the design and overcome the limitation of previous EBG based filter designs. The performance of the proposed filter makes it a viable replacement lumped element filters as it takes up a similar area, displays comparable performance, and saves added BOM cost.

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