Power Plane Filter Using Higher Order Virtual Ground Fence

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Abstract—The virtual ground fence (VGF) has been recently proposed to filter power plane noise in gigahertz frequency range. The VGF has distinct advantages over existing approaches, such as power islands and electromagnetic bandgap structures: The IR drop is not increased; transmission-line return-path discontinuities can be avoided; and the design procedure is simple. The basic VGF is created by using quarter-wave resonators referenced to the power or the ground plane. At the design frequency, the resonator creates an ac short circuit between the power and ground planes. An array of such resonators can be placed in electrically short intervals to create a VGF. Power plane noise will then ideally be shorted to ground at the location of the VGF. The operation principle is similar to the series resonance of a decoupling capacitor, which is usually ineffective in the gigahertz frequency range. This paper proposes a new design procedure for determining the number of quarter-wave resonators needed, their characteristic impedances, and their placement on the board. The design approach is based on the well-known insertion loss method in microwave filter theory, which allows for higher order VGF designs consisting of multiple rows of resonators.

Index Terms—Materials characterization, power and ground planes, power distribution network, power integrity, simultaneous switching noise.

I. INTRODUCTION

Simultaneous switching noise is a major bottleneck in designing robust electronic systems. The traditional approach to suppress noise generated by switching circuits is using decoupling capacitors. However, the equivalent series inductance of discrete capacitors and the inductance of vias used for mounting the capacitors make them unsuitable for providing noise isolation at higher frequencies than a few hundred megahertzes. This is especially a problem for analog/RF circuits sharing the same power supply as the noisy digital circuits.

Most packages and boards make use of power and ground planes in the power distribution network. This is a necessity for providing low IR drop and return paths for transmission lines. The power and ground planes carry not only the dc voltages, but also the switching noise across the board. Therefore, there has been great interest in filtering power plane noise [1]. A commonly used method is based on creating power islands that are connected to the rest of the power plane with a conducting bridge [2], [3]. Recently, periodic structures called electromagnetic bandgap (EBG) structures have been proposed to address power filtering of gigahertz switching noise [4]–[7]. An EBG structure looks like many power islands connected in a 2-D periodic pattern. Due to the narrow bridges connecting the power islands, these approaches require careful planning with regards to the IR drop and current return paths. The virtual ground fence (VGF) introduced in [8] does not suffer from IR drop or current return-path issues as it does not require patterning of the power plane, except a few via holes. The resonators can be designed as microstrip lines or striplines [9], or as semilumped elements [10].

Initial VGF designs were based on a single array of 50-Ω transmission lines behaving as quarter-wave resonators at the design frequency, which can be adjusted simply by changing the length of the resonators [8]. The higher order VGF has been introduced in [11], which can be considered as a 2-D quarter-wave open-circuit stub filter, as shown in Fig. 1.
In this paper, we adopt this traditional filter design approach to VGF. However, we consider that a power filter does not require impedance matching unlike a traditional microwave filter. We study the dependence of VGF performance on several design options, such as the filter order, filter impedance, filter separation, board width, and board thickness. We also present a new methodology for accurate characterization of dielectric thickness, constant, and loss tangent for simulation to hardware correlation of VGF. Finally, a comparison to EBG structures is provided in terms of bandwidth and signal integrity impact.

II. HIGHER ORDER VGF DESIGN METHODOLOGY

We design the VGF based on the common bandstop filter design approach using quarter-wave open-circuit stubs. In Fig. 1, a third-order filter implementation is shown as an example. This can be considered as a parallel connection of many bandstop filters. The open stubs in each row need to be placed in electrically short intervals so that \( d \ll \lambda \). This ensures that plane waves between port 1 and port 2 need to go through the filter structure. Port 1 and port 2 can be considered as the location of a digital IC and RF/analog IC in a practical application.

The characteristic impedances of the stubs can be obtained using the formula

\[
Z_{0n} = \frac{4Z_0}{\pi g_n \Delta}
\]  

where \( Z_{0n} \) is the characteristic impedance of the \( n \)th stub in a row, \( g_n \) is obtained from the table of prototype filter elements, and \( \Delta \) is the fractional bandwidth of the filter. \( Z_0 \) would correspond to the characteristic impedance of the parallel-plate transmission-line section beneath the open stub. \( Z_0 \) would increase as the number of rows increases, so \( Z_0 \) is inversely proportional to \( d \). To obtain a large fractional bandwidth \( \Delta \), small characteristic impedance \( Z_{0n} \) is desirable in addition to large \( Z_0 \).

All the stubs are quarter-wavelength, as shown in Fig. 1. Microstrip stubs with different widths will have different physical lengths due to the change in the effective dielectric constant. The separation \( s \) between each resonator also needs to be quarter-wavelength. Here, the wavelength would correspond to a signal between the power and ground planes. Hence, in general, stub lengths are going to be somewhat longer than the separation between the rows, if the same dielectric material is used in all layers in the board.
The design procedure can then be summarized as follows.

1) Choose a prototype filter type and order (e.g., the third-order, 3-dB equiripple) to obtain $g_n$.
2) Choose $d$ that satisfies $d \ll \lambda$. As a rule of thumb, $d = \lambda/10$ can be used.
3) Find the largest stub width $w_n$ that can be realized on the board. Calculate the characteristic impedance $Z_{0n}$ for that stub. All other characteristic impedances can then be obtained proportionally by properly scaling with the coefficients $g_n$.
4) Obtain all the stub lengths and separation $s$ between the resonators as quarter-wavelength distances.

To illustrate the effectiveness of the VGF, test coupons have been measured and compared with a baseline board consisting of solid power and ground planes. The VGF design is based on a third-order 3-dB equiripple filter consisting of ten rows designed at 2 GHz. Top view of the 60 $\times$ 85.1-mm$^2$ layout is shown in Fig. 2. Two ports close to two top corners have been defined. Measurements were taken using microprobes.

Fig. 3 shows the improvement in isolation between port 1 and port 2 by 40 dB by introducing the higher order VGF at the design frequency. As an application example, an RF circuit at port 2 operating at 2 GHz would be isolated from the noise generated by a digital circuit at port 1. The bandwidth of the VGF is 300 MHz, if an absolute threshold value of 40-dB isolation is defined. By simply adjusting the lengths and spacings of the resonators, the design can be adjusted for a different operating frequency.

### III. SIMULATION TO HARDWARE CORRELATION

The measured boards consisted of a prepreg between microstrip stubs and power plane and a core substrate between the power plane and ground plane. The nominal thicknesses were 120 $\mu$m for the prepreg and 360 $\mu$m for the core. The board material is FR-4 with a nominal dielectric constant of 4.6 at 1 GHz as supplied by the board vendor. The loss tangent is not provided. To accommodate any deviations from the nominal values, it is important to extract the thickness, dielectric constant, as well as the loss tangent of the dielectrics. We designed simple shorted cavity resonators of size 40 $\times$ 40 mm$^2$ following the methodology in [12] and [13], as shown in Fig. 4. In this paper, we extended the automated extraction methodology in [13] by defining the dielectric thickness as one of the free variables as well.
Fig. 7. (a) Layout of two VGF designs with different resonator characteristic impedances. (b) Lowering the resonator impedances by using wider traces improves VGF performance.

The extracted parameters for the prepreg were the thickness of 153 μm, the dielectric constant of 4.16, and the loss tangent of 0.024. For the core layer, the same parameters were extracted as 371 μm, 4.66, and 0.018. Using the extracted parameters, the shorted cavity resonator was simulated using the full-wave simulator Sonnet [14]. Fig. 4 shows excellent match between the simulation and the measurement.

We apply the extracted parameters on the simulation of the VGF, as shown in Fig. 5. The good agreement indicates the accuracy of the extracted dielectric thickness, loss tangent, and dielectric thickness of the core and prepreg layers.

IV. DESIGN OPTIONS FOR HIGHER ORDER VGF

The bandwidth and the level of isolation depend on several design options, such as the filter order, filter impedance, filter separation, board width, and board thickness in the VGF. In Sections IV-A–IV-E, we discuss the influence of these design options on the performance of the VGF.

A. Filter Order

Fig. 6 shows the effect of filter order on the VGF performance. The first-, third-, and fifth-order VGF designs are compared. It can be observed that a higher order VGF improves both isolation level and bandwidth. However, it requires more area possibly increasing the board size, as it was the case with the fifth-order VGF board.

B. Filter Impedance

Fig. 7 shows the effect of resonator characteristic impedance on the VGF performance. Two third-order VGF designs are compared to a middle resonator width of 200 and 600 μm. Other resonator widths are then scaled proportionally based on (1). It can be observed that lowering the resonator impedances by using wider traces improves VGF performance. However, the resonators cannot be made arbitrarily wide, as there should be room for signal traces to cross the board from one side of VGF to the other side.

C. Filter Separation

The VGF is based on periodically repeating a 1-D filter to fill a 2-D board. The distance $d$ between each row needs to be electrically short to prevent any noise leakage across the VGF. Fig. 8 shows two cases where each 1-D filter occupies a width of 4 or 6 mm. The characteristic impedance $Z_0$ of the
parallel-plate transmission line assigned to each row increases by using more rows. As $Z_0$ increases, the bandwidth $\Delta$ of the filter should increase following (1). Fig. 8 confirms the increase in bandwidth. Once again, there is a tradeoff with leaving room for signal traces.

D. Board Width

The VGF should provide power filtering for any board width. For narrower boards, a few rows of VGF should be sufficient. One example is shown in Fig. 9, where different board widths are studied, such that one, two, or ten rows of VGF were needed to fill the board. Fig. 9 shows that VGF provides power filtering for all three cases at the design frequency of 2 GHz.

E. Board Thickness

Varying the dielectric thickness between the power and ground planes would shift the bandgap frequencies of the conventional planar EBG structures. An advantage of the VGF is that the same design works for different dielectric thicknesses. A case is studied where the same VGF design in Fig. 2 is used on a board with a core thickness of 787 $\mu$m. The comparison to the thinner core of 371 $\mu$m is shown in Fig. 10. It can be seen that the VGF works also for the thicker core, and even with a better bandwidth. The characteristic impedance $Z_0$ of the parallel-plate transmission line assigned to each row increases by using thicker dielectrics. As $Z_0$ increases, the bandwidth $\Delta$ of the filter should increase following (1) as observed in Fig. 10.

V. Comparison With EBG Structures and Signal Integrity Consideration

Fig. 11 shows the comparison between a 1-D EBG structure and one-row VGF implemented on the thicker core of 787 $\mu$m.
VI. CONCLUSION

A new power plane filter design based on higher order VGF has been presented. Classical microwave filter design procedure has been extended to planar structures. The presented VGF has a simple design approach based on established microwave bandstop filter methodology, unlike the complicated planar EBG or power island designs that typically require electromagnetic simulations. In all studied cases, the VGF was able to provide isolation at the design frequency. Full-wave simulations confirm the accuracy of the measurements after careful extraction of dielectric thickness, constant, and loss tangent. The VGF requires minimal modifications on the existing power and ground planes, which, therefore, does not increase IR drop. It has also been shown that transmission lines have continuous return paths and the insertion loss is similar to a baseline board without VGF. Therefore, this new approach provides a robust methodology to provide power plane filtering in mixed-signal designs, which has not been possible with the existing power island or planar EBG designs.

REFERENCES

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