Nonoverlapping Power/Ground Planes for Suppression of Power Plane Noise

Arif Ege Engin, *Member, IEEE*, Ivan Ndip, *Senior Member, IEEE*, Klaus-Dieter Lang, *Senior Member, IEEE*, and Gerardo Aguirre, *Senior Member, IEEE*

***Abstract*— Providing low *IR*-drop and inductance are two major roles of power and ground (PG) planes in chip packages and boards. However, planes can also cause switching noise coupling, especially when they resonate. This is a concern for mixed-signal boards, high-speed I/Os, and electromagnetic compatibility. Discrete decoupling capacitors are ineffective to control switching noise at gigahertz frequency regime due to their inductance. To filter such high-frequency noise, a possible approach is modifying the shape of the PG planes, such as in power islands or electromagnetic bandgap structures. In this paper, we introduce the nonoverlapping PG planes design methodology for filtering of gigahertz power plane noise. Unlike existing approaches, our approach is simple and has wide bandwidth, while avoiding narrow inductive bridges that increase *IR*-drop.**

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

I. Introduction

CHIP packages and printed circuit boards make use of power/ground (PG) planes to improve power integrity in two main aspects. They provide a low resistance (i.e., low *IR*-drop) connection from the chip terminals to the power supply. To control *IR*-drop, multiple PG layers in a stack-up with thick metals can be used. At higher frequencies, the same PG planes can also provide a low inductance connection to the off-chip decoupling capacitors if PG layers are stacked in an alternating manner. On many package and board stack-ups, it is, therefore, a common practice to allocate several layers in an alternating manner to PG planes.

Low *IR*-drop and low inductance properties of PG planes do not, however, necessarily provide low impedance at higher frequencies. PG planes cause undesirable antiresonances, as they interact with the decoupling capacitors or when their sizes exceed half a wavelength. This high impedance is especially a concern for mixed-signal boards, high-speed I/Os, and electromagnetic compatibility. In a mixed-signal board, the sensitive analog/RF circuits may require high levels of isolation from switching noise. High-speed I/Os may experience crosstalk noise coupled globally through the PG planes. Finally, edge radiation from PG planes is one of the main sources for electromagnetic interference. The coupling of switching noise in these cases depends on the transfer impedance of the power distribution network.

Traditional solution to control switching noise is based on decoupling capacitors, which, however, become ineffective due to their inductance in gigahertz frequency regime. Therefore, special patterned power planes, such as power islands/archipelago [1], [2] or electromagnetic bandgap structures [3]–[6], have been used to reduce the transfer impedance. These designs provide a low-pass filter response by generating capacitive patches on the power plane connected by narrow inductive bridges. These narrow bridges, however, significantly increase the *IR*-drop of PG planes and result in signal integrity issues for I/Os that need to run over slits in the power plane. Another approach is based on using quarter-wave resonators as a distributed substitute for discrete decoupling capacitors. At the design frequency, the resonators create an ac short circuit between the PG planes. An array of such resonators then can be placed in electrically short intervals to create a virtual ground fence [7]–[10]. This bandstop-type filter is mostly suitable for narrowband systems due to the nature of quarter-wave resonators.

In this paper, we discuss the nonoverlapping PG (no-PG) planes design methodology for filtering of gigahertz power plane noise. This approach directly controls the coupling of switching noise globally on a package or board. The design procedure is simple and results in broadband isolation. It is based on using traditional alternating PG layers for designing locally the power distribution network of each IC on a board. The local power distribution networks are connected with each other using no-PG planes that provide ultimate noise isolation. The presented no-PG planes design methodology for the first time provides broadband filtering of power plane noise while avoiding narrow inductive bridges that increase *IR*-drop. The basic design approach for no-PG planes has been introduced in [11]. In this paper, we present design options for the no-PG planes depending on the board size, port location, segment separation, and segment size.

II. Nonoverlapping Power/Ground Planes

A typical four-layered board stack-up is shown in Fig. 1(a). The closely spaced PG planes are desired for low inductance

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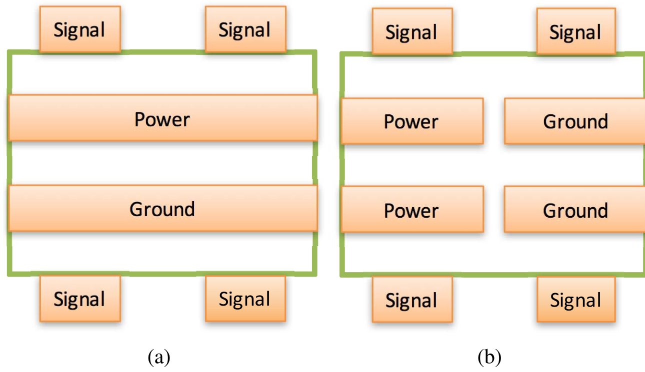


Fig. 1. (a) Traditional PG layers in a typical four-layered board. (b) no-PG layers designed as PP or GG layers.

Fig. 2. Example layout with 3×2 PG segments that would be interconnected with low *IR*-drop, but isolated from each other at high frequencies due to PP and GG segments.

connection of off-chip decoupling capacitors. Therefore, it is assumed that locally each IC on a multichip board will be placed on top of traditional alternating PG layers. The PG planes in this layer stack-up, however, behave as parallel-plate waveguides and allow propagation of switching noise globally across the whole board, especially at the antiresonance frequencies. To completely eliminate the parallel-plate currents, we propose to use power/power (PP) and ground/ground (GG) segments in the stack-up, as shown in Fig. 1(b). The no-PG plane segments in the form of PP or GG planes globally filter switching noise.

The PP and GG segments are used to serve as isolating elements among PG segments while preserving dc connectivity in the layout. An example layout could then look, as shown in Fig. 2, where there are 3×2 PG segments that would be interconnected with low *IR*-drop, but isolated from each other at high frequencies. Any small gaps, such as the two empty squares in the example layout, can then be filled with PP or GG segments. Although the example is given for a single PG plane pair, this new design approach can be extended to designs with arbitrary number of PG layers.

III. Example Design

To demonstrate the performance of no-PG planes, a two-layered board was designed, as shown in Fig. 3. The board

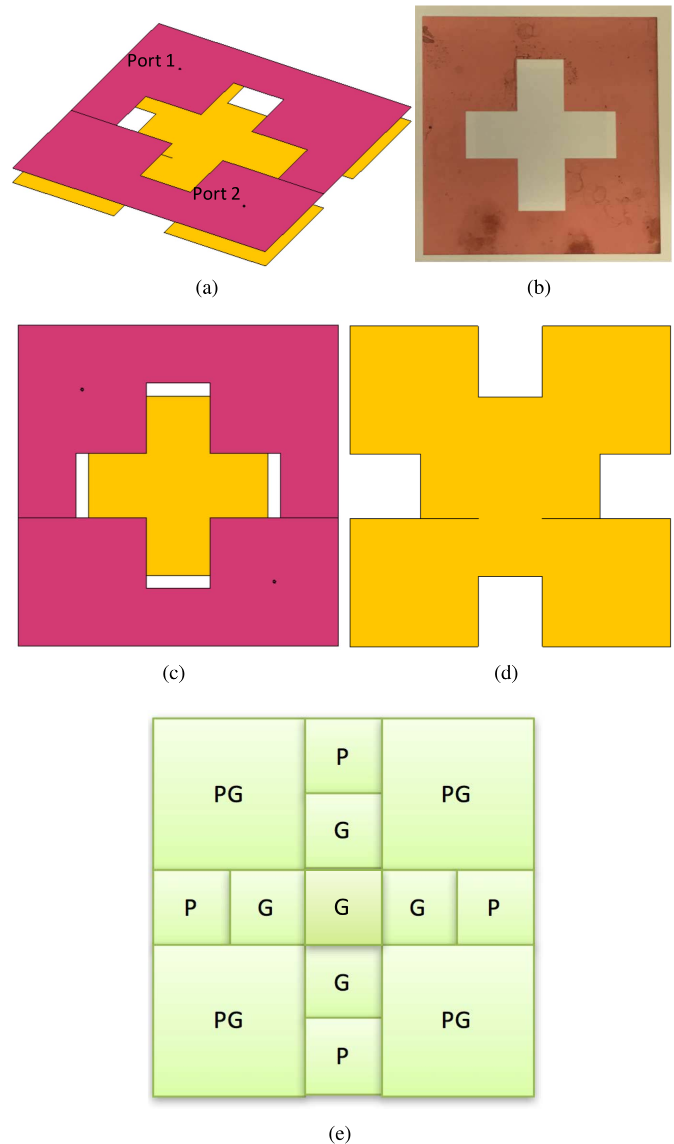
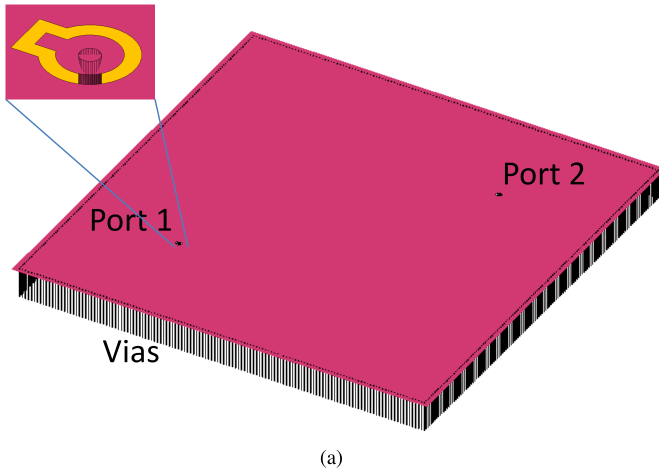


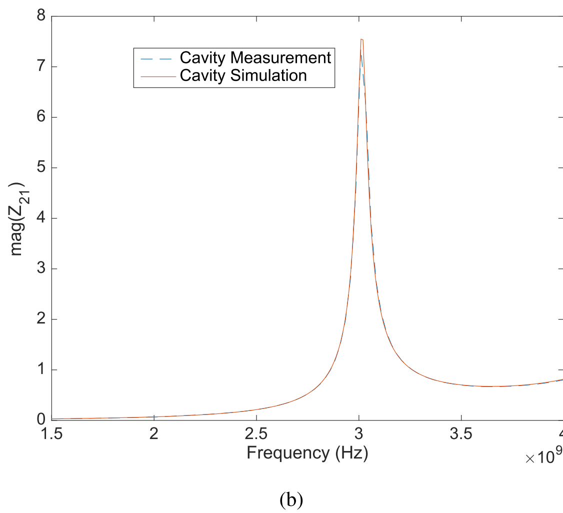
Fig. 3. LCP board with no-PG planes. (a) 3-D view. (b) Picture of the test coupon. (c) Top view. (d) Ground plane. (e) Corresponding layout segmentation with 2×2 PG segments isolated from each other at high frequencies due to P and G segments.

consists of 2×2 PG segments that are interconnected with P and G segments. In this design, P and G segments were preferred to be able to easily visualize the concept. The isolating P and G segments could be extended to PP and GG segments, respectively, using vias to maintain low *IR*-drop.

In a practical board design, PG planes can come in arbitrary shapes and include cutouts or via holes. For such arbitrary plane shapes, the same design principles can be applied as well, by avoiding the overlap of PG planes in isolating segments. The signal integrity of transmission lines also needs to be considered. There will be a return path discontinuity for transmission lines running over cut regions. However, this problem is not as severe as in electromagnetic bandgap structures or power islands that require narrow bridges. The wide P and G segments can allow a continuous wide return path for transmission lines running across isolated segments.



(a)



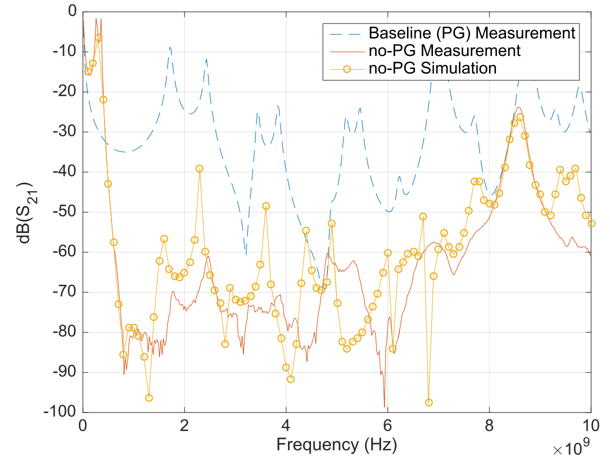
(b)

Fig. 4. (a) Cavity resonator of size 4.05 cm × 4.05 cm to extract the dielectric thickness (DT), constant (DK), and loss tangent (DF). The inset shows the zoomed-in-view area around the measurement port. (b) Simulation to hardware correlation for DT = 100 μm, DK = 2.98, and DF = 0.004 for LCP core.

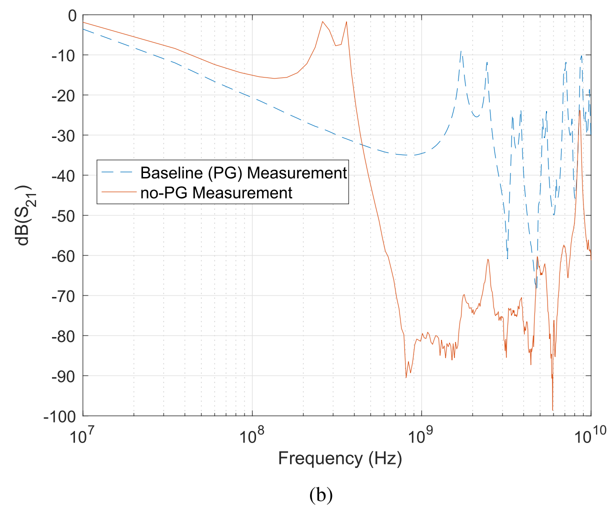
An interesting aspect of this new stack-up is the via transitions of transmission lines through isolating PP and GG segments. Unlike traditional PG segments, the current return path discontinuity would be small, as both transmission lines would be referenced to the same voltage plane.

A. Simulation to Measurement Correlation

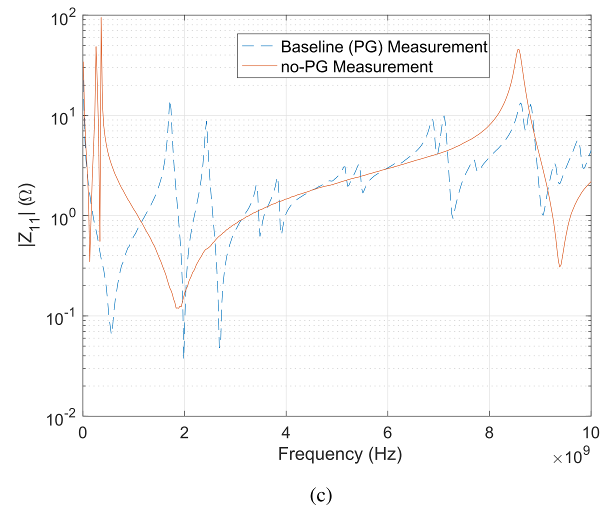
The no-PG planes design has been implemented on a liquid crystalline polymer (LCP) board. For verification of measurements with simulations, we extracted the materials properties using simple shorted cavity resonators of size 4.05 cm×4.05 cm following the methodology in [12] and [13], as shown in Fig. 4. The extracted parameters for the LCP core were thickness of 100 μm, dielectric constant of 2.98, and loss tangent of 0.004. Using the extracted parameters, the shorted cavity resonator was simulated with the full-wave simulator Sonnet [14]. Fig. 4 shows excellent match between simulation and measurement.



(a)



(b)



(c)

Fig. 5. (a) Simulation to hardware correlation for no-PG planes. Measurements indicate more than 50-dB isolation from 0.6 to 8 GHz for the no-PG design, eliminating the high level of coupling of the baseline case consisting of solid PG planes. (b) Same measurements plotted without the simulation data in logarithmic scale for clarity. (c) Measured input impedance of the no-PG design shows suppressed cavity resonances in its stopband.

We then used these extracted parameters to simulate the no-PG planes design in Fig. 3. The total size of the board is 5 cm × 5 cm. Measurements were taken using microprobes

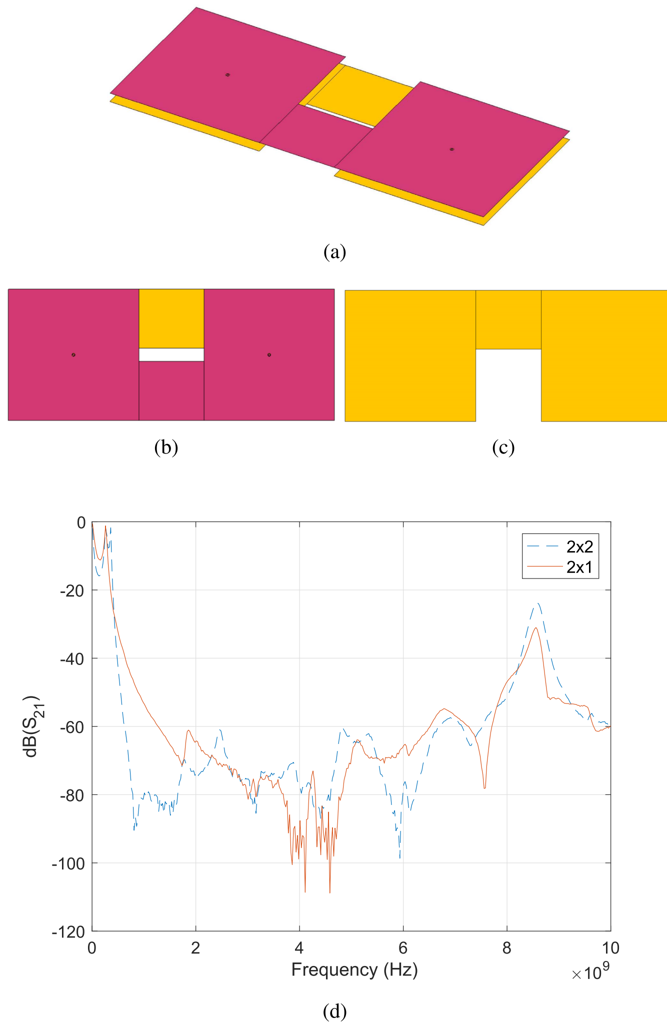


Fig. 6. Smaller board of size 5 cm × 2 cm consisting of 2 × 1 segments. (a) 3-D view. (b) Top view. (c) Ground plane. (d) Measured isolation level is similar to the larger 2 × 2 board in Fig. 3.

by isolating the board from the measurement chuck using a 3-mm-thick plexiglass. Simulations predict accurately the on-set and off-set frequencies for the isolation bandwidth, as shown in Fig. 5(a). Measurements indicate more than 50-dB isolation from 0.6 to 8 GHz for the no-PG case, while there is a high level of coupling for the baseline case consisting of solid PG planes. This bandwidth for isolation is outstanding and typically not achievable using existing approaches, such as power islands/archipelago, electromagnetic bandgap structures, or virtual ground fence. As an example, the electromagnetic bandgap structure in [3] has 30-dB isolation from 1.76 to 9.72 GHz and may cause signal integrity problems due to return path discontinuity.

Outside of the isolation frequency band, the coupling could actually increase, as shown in Fig. 5(b), plotted again in logarithmic scale for better clarity. The crossover where the no-PG case has more isolation than the solid PG planes occurs at approximately 450 MHz. Fig. 5(c) shows the magnitude of the input impedance of the no-PG case, which suppresses the cavity resonances in its stopband. Its input impedance,

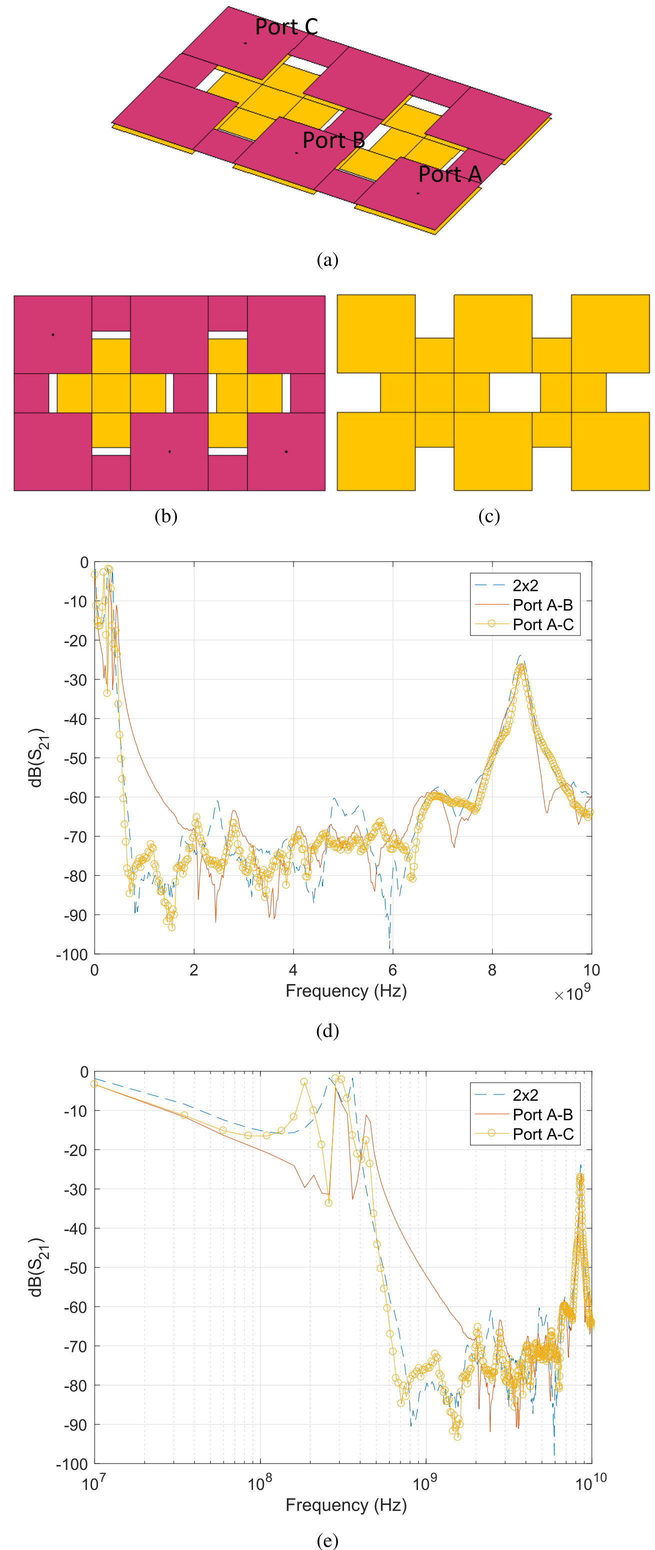


Fig. 7. Larger board of size 8 cm × 5 cm consisting of 3 × 2 segments. (a) 3-D view. (b) Top view. (c) Ground plane. (d) Port location has primarily an impact on the on-set frequency of the stopband. (d) Same measurements plotted in logarithmic scale for clarity at lower frequencies.

however, exceeds the impedance of solid PG planes at lower frequencies. The test boards did not include any decoupling capacitors, which can address some of the coupling and increased impedance issues at these lower frequencies.

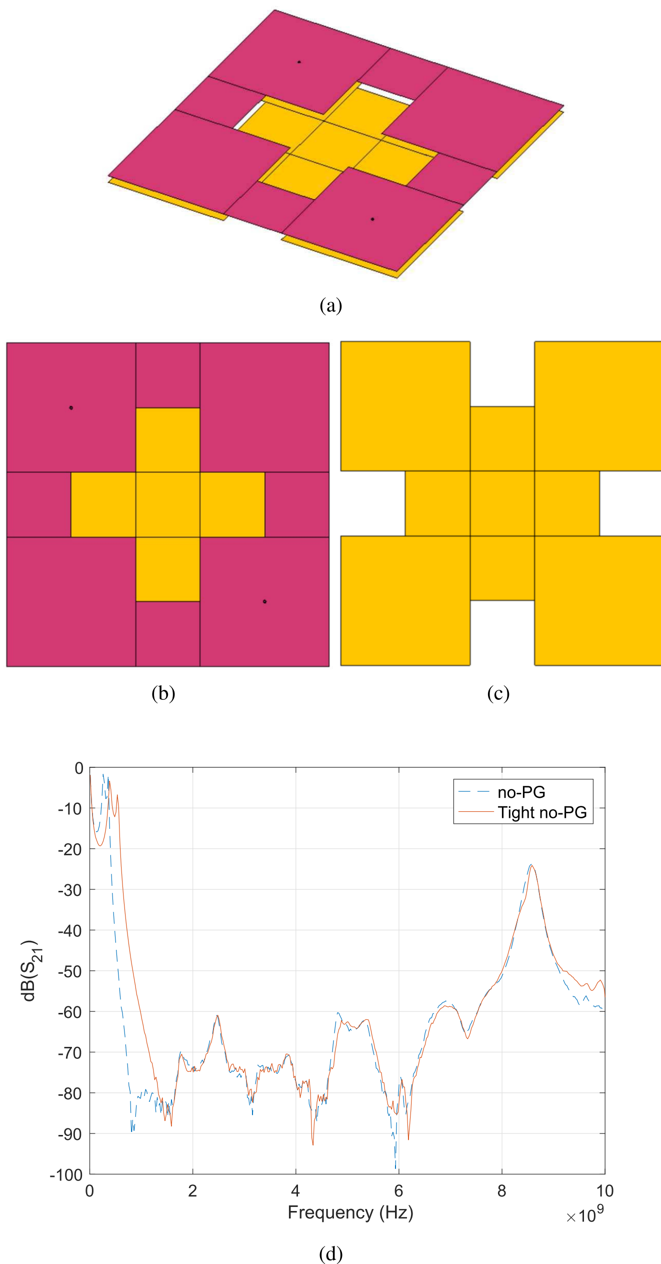


Fig. 8. Tight design of P and G segments with no gaps. (a) 3-D view. (b) Top view. (c) Ground plane. (d) Gap capacitance only has an impact on the measured on-set frequency of the stopband.

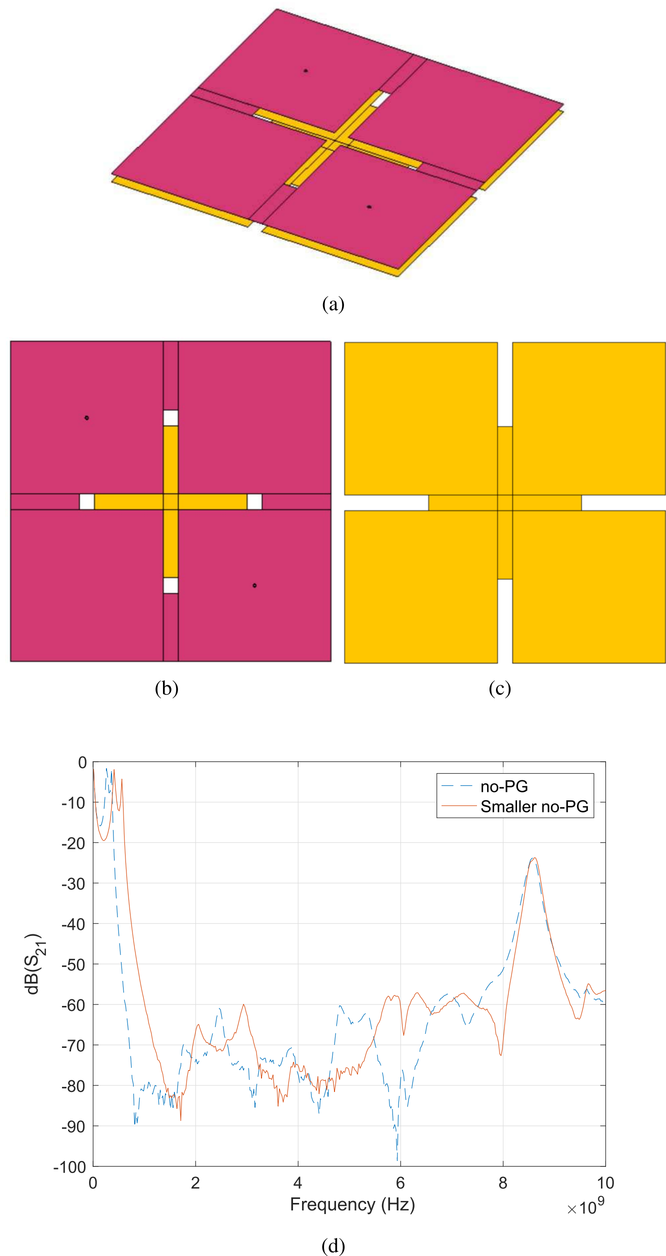


Fig. 9. Design with shorter isolating segments. (a) 3-D view. (b) Top view. (c) Ground plane. (d) Shorter segments primarily affect the measured on-set frequency of the stopband.

IV. Design Options

The design of the no-PG planes is going to depend on the board size, port location, segment separation, segment size, and *IR*-drop considerations. Next, we investigate the impact of these parameters on the performance of the PG planes. The following results are the measurement data of the same test coupon in Section III.

A. Board Size

A rectangular-sized board of size 5 cm $\times$ 2 cm is considered, as shown in Fig. 6. This design consists of 2×1 PG segments, and hence, the isolation is provided by a single isolating segment. However, the resulting isolation level is similar to the larger 2×2 board in Fig. 3. Unlike EBG designs that require multiple unit cells to achieve high levels of isolation, this example demonstrates that a single isolating P and G segment is already effective to filter the power plane noise.

B. Port Location

A larger board of size 8 cm $\times$ 5 cm with 3×2 PG segments is considered, as shown in Fig. 7. High isolation is achieved among various PG segments. The on-set frequency of the stopband is smaller when ports are farther from each other. In this case, the connection is achieved through multiple P and G segments. The measured off-set frequency of the stopband was similar for different port locations.

C. Segment Separation

There is an intentional gap between P and G segments in the no-PG design as seen from the top view in Fig. 3(c) to reduce

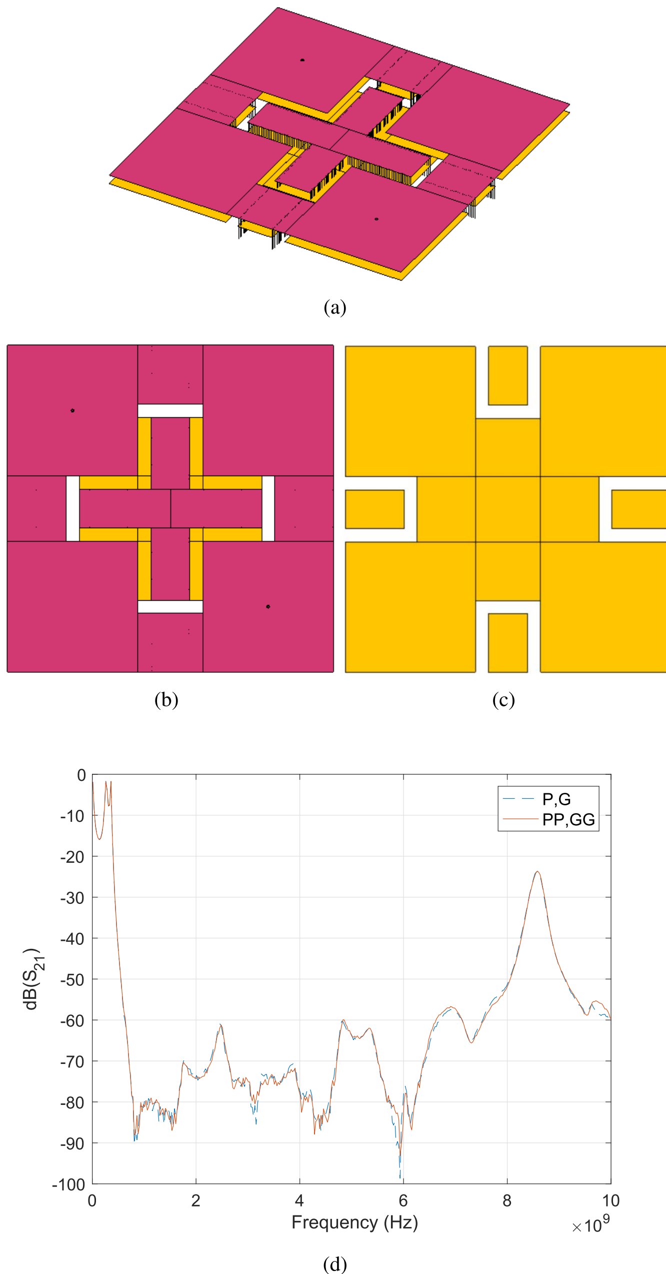


Fig. 10. Design with PP and GG segments to reduce *IR*-drop compared to the P and G segments in Fig. 3. (a) 3-D view. (b) Top view. (c) Ground plane including four small patches for power. (d) PP and GG segments should reduce *IR*-drop without affecting the high-frequency performance.

any parasitic gap capacitance from power to ground planes. To investigate the impact of this gap capacitance, a tight design is considered in Fig. 8, where the gaps have been removed. The results suggest that the gap capacitance only has an impact on the on-set frequency of the stopband, as shown in the figure.

D. Segment Size

The length of the isolating PP and GG segments can be made shorter if necessary. A modified design with smaller segments is considered in Fig. 9, where the overall size of the board has been reduced to 4.2 cm $\times$ 4.2 cm due to the shorter isolating segments. The length of the isolating sections primarily has an impact on the on-set frequency of the stopband, as shown in the figure.

E. Low IR-Drop

The lowest *IR*-drop would be achieved for solid PG planes. Due to the cut-outs in P and G segments, their *IR*-drop would double compared to the solid PG planes, assuming a tight design and neglecting current crowding. This increase will, however, not be as significant as the *IR*-drop through electromagnetic bandgap structures or power islands, which require narrow P segments. To further reduce *IR*-drop, PP and GG segments can be used as in Fig. 10 instead of P and G segments as in Fig. 3. The planes in PP and GG segments are shorted with each other using many vias. This provides a parallel current path for dc currents, which helps the *IR*-drop to approach that of solid PG planes, neglecting via resistance and current crowding effects. The presence of these vias and plane segments does not affect the high-frequency performance, as shown in Fig. 10.

To summarize, all considered design options provided similar isolation performance with the exception of the on-set frequency of the stopband, demonstrating the versatility of using no-PG planes.

V. Conclusion

An outstanding isolation level and bandwidth has been demonstrated using no-PG planes. This simple approach overcomes some of the major shortcomings of existing approaches for gigahertz power integrity as it does not require narrow power plane bridges that increase *IR*-drop and cause return path discontinuities. Isolation of gigahertz noise coupling through the PDN has been observed for various design options, indicating a robust design approach that does not require complex electromagnetic analysis. Segmenting the PG planes using this approach can allow localized PDN design, radically simplifying the current PDN design processes.

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