2023 IEEE Symposium on Electromagnetic Compatibility & Signal/Power Integrity (EMC+SIPI) | 979-8-3503-0976-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/EMCSIPI50001.2023.10241719

# Undesired-resonance Analysis and Modeling of Differential Signals Due to Narrow Ground Lines Without Stitching Vias

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***Abstract*—Undesired resonances on high-speed differential signals are studied in this paper, which is caused by the adjacent narrow ground line without stitching vias. Due to space limitations in the high-speed channel layouts of certain package applications, the ground (GND) line is often narrow and has insufficient stitching vias, potentially causing undesired resonance in high-speed differential signals. In this study, these undesired resonances were investigated using 3D simulations, revealing that they can be modeled as parallel-coupled half-wavelength resonance. The resonance frequency of the parallel-coupled half-wavelength resonance structure can be predicted well using the formula based on the GND line length. Moreover, three potential solutions to undesired resonance are proposed, providing a practical guide for GND line routing in specific applications.**

***Keywords: resonance, differential signal, half-wavelength resonator, fan-out, package application.***

## I. Introduction

With the ongoing miniaturization of technology and dramatic increases in data-rate demands, increasing numbers of modules are being integrated into small devices. The resulting space limitations make the layout of high-speed channels for high-density interconnects (HDIs) more challenging than ever. Maintaining good signal integrity is necessary for printed circuit board (PCB) designers to meet product development goals and reduce overall costs [1], especially for package and chip applications.

For example, escape wiring in flip-chip areas is complex; the main challenge being maintaining the ground (GND) reference for the signal trace while also leaving voids in the same area to accommodate digital and analog power build-up vias. In order to reduce pair-to-pair crosstalk, a GND shielding line between differential pairs starting from the flip-chip area is used. However, the need for compact layouts have made it more common for the GND line to be narrow and have insufficient stitching vias. Narrow GND lines can cause undesired resonance in high-speed signals. Undesired resonance due to non-ideal return-path design for high-speed differential pairs is introduced in Wang et al. [2], and Liu et al. proposed a quarter-wavelength resonance model to analyze undesired resonance [3]. Furthermore, unintentional resonances in high-speed signals can be produced by non-ideal routing GND stubs [4].

In this study, undesired resonances in differential signals are studied based on 3D full-wave simulations. We found that undesired resonances can be observed when a narrow GND line without stitching vias is adjacent to the signal trace. From the 3D simulation, the undesired resonances can be modeled as parallel-coupled half-wavelength resonance, while the structure of a signal trace with an adjacent narrow GND line is represented by a parallel-coupled half-wavelength resonator.

According to our results, three potential solutions to mitigate undesired resonances are proposed: i) increasing the distance between the signal trace and the narrow GND line; ii) adding stitching vias on the GND line; or iii) deleting the GND line. The benefits and limitations of each are discussed, providing a useful resource for engineers engaged in the design of GND line routing for specific applications.

## II. Undesired Resonance Issue

This section introduces undesired resonances in differential pairs with compact layouts. The differential insertion losses of three channels with undesired resonance at several frequencies are presented.

### *A. Compact High-speed Pair Layouts*

Generally, the layout of high-speed differential pairs must be very compact due to space limitations. Figure 1 (a) shows the

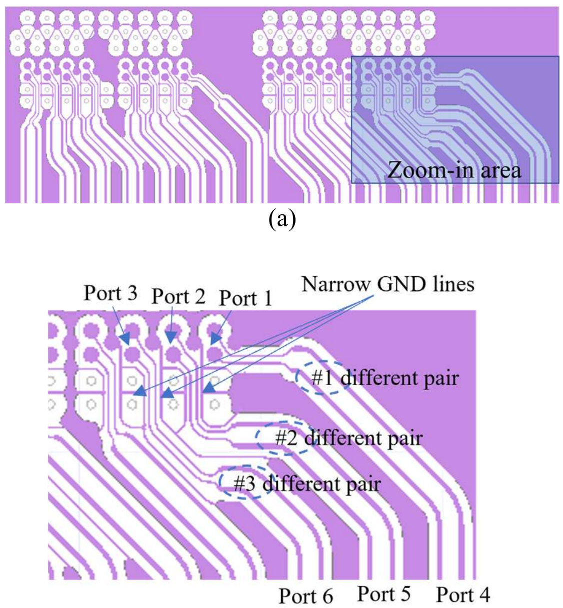
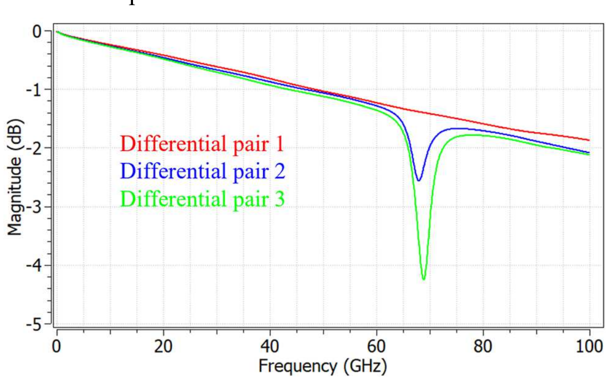



Fig. 1. Top view of a compact differential pair layout. (a) Full differential pair layout; and (b) zoom-in area in (a).

layout of several differential pairs, which are routed on an 8-2-8 organic substrate board with 18 copper layers for the co-packaged optics module. The layout is complicated and dense. Three differential pairs are expanded to show the undesired resonances. As shown in Figure 1(b), several GND lines are placed adjacent to the differential pairs to reduce crosstalk between them. Furthermore, the GND lines and signal traces close to the transition vias are narrow due to the limited layout space. Here, the signal trace and the GND line widths three are all 12 µm. Six differential ports are defined for the selected differential pairs, as shown in Figure 1(b).

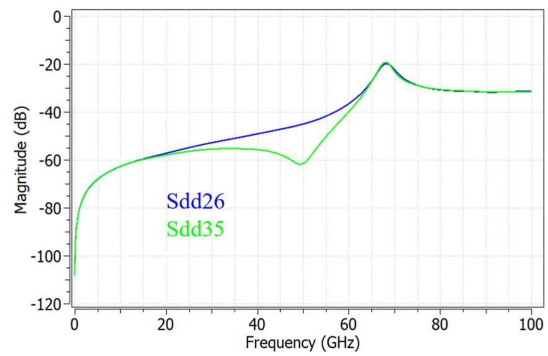
## *B. Undesired Resonance in Differential Signals*

The three differential pairs shown in Figure 1(b) were simulated using Ansys High-frequency Simulation Software (HFSS). Figure 2(a) shows the differential insertion losses for the three differential pairs up to 100 GHz, revealing undesired resonances for pairs 2 and 3. This is because there are narrow GND lines adjacent to differential pairs 2 and 3, but not to differential pair 1.




(a)

Fig. 2. (a) Differential insertion loss.



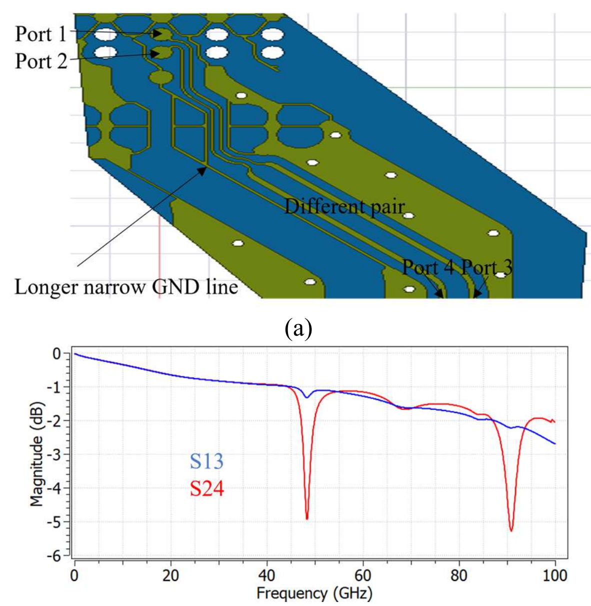

(b)

Fig. 2. Continues: (b) Far-end crosstalk.

Figure 2(b) shows the far-end crosstalk between differential pairs 2 and pair 3. Undesired resonances are observed at the same frequency. The data rate for the co-packaged optics module is 224 Gbps, which has a Nyquist frequency of 56 GHz with PAM4 modulation. These resonances in insertion loss and crosstalk close to the Nyquist frequency have a significant impact on performance and must be eliminated through rational and well-informed layout design.

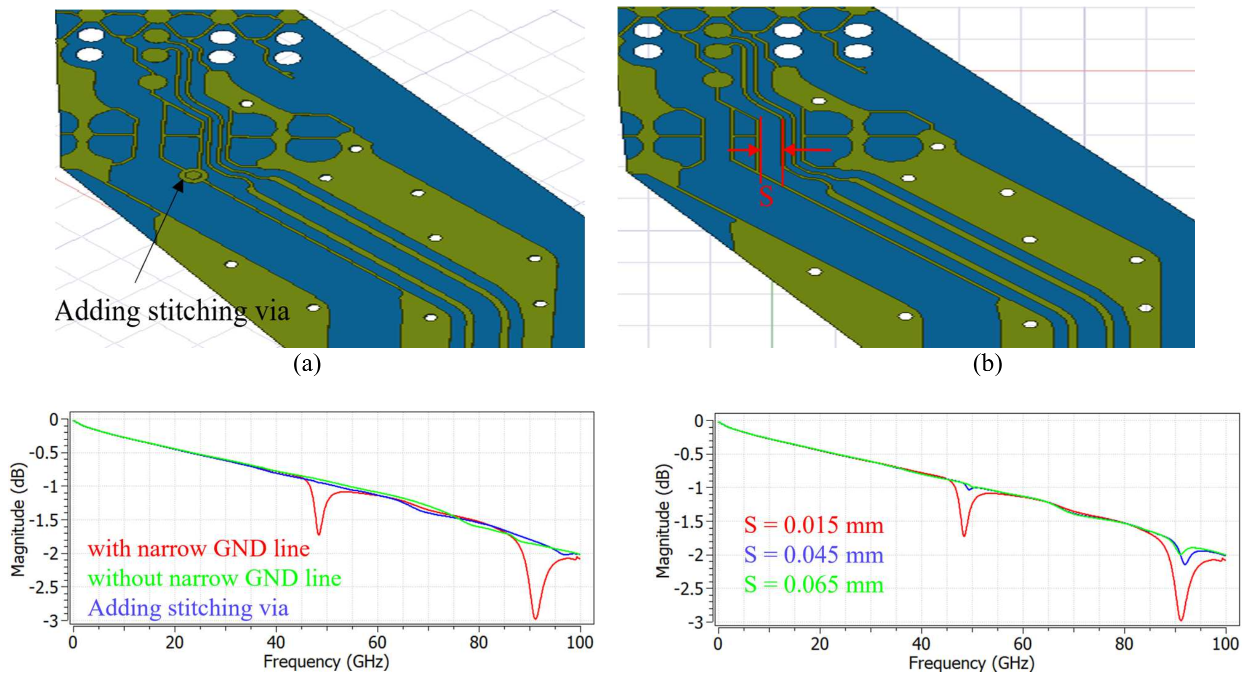
## III. Analysis, Modelling, and Solutions

In this section, undesired resonances are investigated based on simulations. The current density in a narrow GND line is simulated and presented. The undesired resonance can be modelled as half-wavelength resonance.




(b)

Fig. 3. (a) Differential pair with a longer narrow GND line. (b) Single ended insertion loss.




(b) (d)
(c)

Fig. 4. (a) Adding stitching via; (b) space between the signal trace and the narrow GND line; (c) differential insertion loss comparison; and (d) differential insertion loss comparison for different S values.

*A. Undesired Resonances Analysis*

To accurately analyze the undesired resonances, another differential pair with one long narrow GND line on the same board is investigated, as shown in Figure 3(a). The ports are also defined in Figure 3(a). The single ended insertion losses of these differential signal traces are plotted in Figure 3(b). The resonance for S24 is stronger than that for S13. This is because the longer narrow GND line is adjacent to the signal trace for ports 2 and 4, further indicating that the resonance is caused by the narrow GND line. The frequency of the first resonance is approximately half that of the second, which means the undesired resonance is periodic. Compared with the previous three differential pairs, the first resonance frequency for this case is small due to the longer GND line.

To confirm that the undesired resonances are caused by the narrow GND line, the differential insertion loss of the differential pair with and without (GND line is deleted) the narrow GND line are compared in Figure 4(c). The undesired resonance disappears when the narrow GND line is deleted. The undesired resonances can also be removed by adding a stitching via on the narrow GND line. As shown in Figure 4(a), one stitching via was added on the narrow GND line. The insertion loss of the differential pair after adding the stitching via is represented by the blue curve in Figure 4(c), showing that the undesired resonances are eliminated.

The undesired resonances are related to the distance between the narrow GND line and the signal trace (S), which is illustrated in in Figure 4(b). The impact of this parameter on undesired resonance was investigated by sweeping S. The undesired resonances can be mitigated by increasing S, as shown in Figure 4(d). The initial value of S is 0.015 mm, the magnitude of the undesired resonance can be dramatically mitigated by increasing S to 0.045 mm, which is approximately four-times the trace width. The resonance is almost eliminated when S is 0.065 mm for this case.

*B. Undesired Resonance Modelling*

The above analysis confirms that the undesired resonances are caused by a narrow GND line placed adjacent to the signal trace. The physical meaning of the undesired resonances is

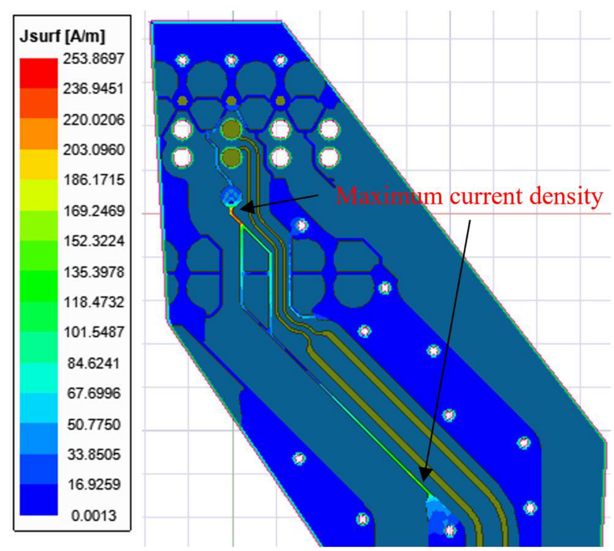



Fig. 5. Current density on the simulated narrow GND line.

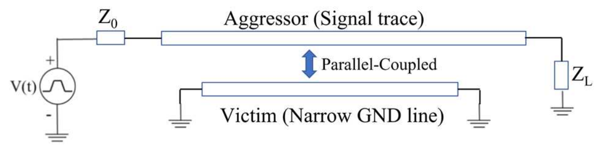



Fig. 6. Equivalent circuit of the parallel-coupled half-wavelength resonance.

analyzed as follows. Figure 5 shows the current density at the resonance frequency for the narrow GND line. The maximum current density is shown at the ends of the GND line, and the minimum current density is at the centre. This shows that the narrow GND line behaves as a half-wavelength resonator, impacting the adjacent signal trace.

The theory of parallel coupling is used extensively in the design of transmission line filters in the microwave field [5]. The basic mechanism of a parallel-coupled transmission-line resonator filter is introduced in [6], where the transmission line is distributed parallel. For the design studied here, the narrow GND line and signal trace are parallel to each other, which can cause parallel-coupled resonance. Note that since the ends of the narrow GND line are shorted to a larger GND plane, it behaves as a half-wavelength resonator. Thus, the whole structure comprising the signal trace and the narrow GND line can be modelled as the equivalent circuit shown in Figure 6. The aggressor line represents the signal trace while the victim line is the adjacent narrow GND line. The parallel-coupled structure (here the signal trace with a narrow GND line) is constructed due to the compact layout. In summary, the undesired resonance is produced by the combined effects of the signal trace and the adjacent narrow GND line.

The undesired resonance frequency for a parallel-coupled half-wavelength resonator can be calculated as follows.

$$f = \frac{c}{\sqrt{\varepsilon_r}}\frac{1}{2l} \tag{1}$$

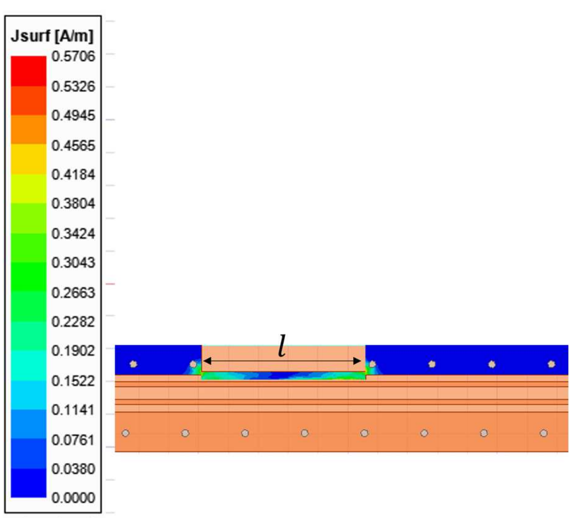



Fig. 7. Simplified parallel-coupled structure.

Table I. Comparison of resonance frequencies for the parallel-coupled resonance structure

| Frequency (GHz) | $l$ (mm) | | |
|---|---|---|---|
| | 2.0 | 1.6 | 1.2 |
| Simulation | 46.8 | 56.4 | 72.9 |
| Calculation | 47.4 | 59.3 | 79.1 |

where $\varepsilon_r$ is the relative permittivity of the dielectric for the board, $l$ is the length of the narrow coupled GND line, and $c$ is the light speed in a vacuum.

To accurately validate the proposed parallel-coupled resonance model, a simplified parallel-coupled structure was used to compare the resonance frequencies from the full wave simulation and the calculation. Figure 7 shows the simplified parallel-coupled structure, where a differential pair is adjacent to a narrow GND line. The current density of the GND line at the resonance frequency is also shown in Figure 7, and it is similar to the real case shown in Figure 5. This indicates that the simplified geometry provides a good representation of the resonance issues observed with the actual design geometry.

The length $l$ of the narrow GND line was swept to obtain the corresponding resonances for the structure. The resonance frequencies from the simulations and calculations based on Equation (1) are compared in Table I; they are similar, but not the same. This is because the effective length of the narrow GND line is not precisely the length $l$. The effective length of the narrow GND line in this case should be the distance between the GND vias at each end of the narrow GND line, which is somewhat longer than the narrow GND line. This means that the distance between two adjacent stitching vias should be less than the half-wavelength of the maximum working frequency avoiding the undesired resonance.

The proposed parallel-coupled resonance model can help us to understand undesired resonance physically. The signal trace is parallel coupled with the narrow GND line, and this also explains how the distance between them impacts the magnitude of the resonance. Adding stitching vias can reduce the effective length of the resonator by reducing the length of the narrow GND line. Thus, the resonance can be removed from the frequency range of interest dictated by the application data rate.

### C. *Three Solutions for Mitigating/Removing Undesired Resonance*

Based on the above analysis, we propose three solutions to remove or mitigate undesired resonance. First, undesired resonances can be removed by deleting the narrow GND lines. However, crosstalk between differential pairs can increase upon deleting these GND lines. The increase in crosstalk upon removing the GND lines depends on the specific model analyzed. For our design, the crosstalk between differential pairs #1 and #2 is increased by 0.5 dB when the GND line is removed.

Secondly, adding stitching vias on the narrow GND line can also help to remove undesired resonance from the frequency bandwidth of interest because the stitching via effectively decreases the resonance length of the GND line. However, this solution requires sufficient available space for adding stitching vias, which is difficult for limited-space layouts.

Thirdly, undesired resonance can be mitigated if the GND line and signal trace are sufficiently distant.

## IV. Conclusion

Undesired resonances in differential signals caused by an adjacent narrow GND line were investigated in this study using 3D full-wave simulations. Our results show that the undesired resonances can be mitigated or removed by increasing the distance between the signal trace and the narrow GND line, adding stitching vias on the GND line, or deleting the GND line. Each solution has its own benefits and limitations, and they may serve as guidelines to help design engineers with GND line routing for different application scenarios in terms of application data rate, routing congestion, and ground shielding location. Moreover, a parallel-coupled half-resonance model was proposed to help understand the physical mechanism of the undesired resonances. The resonance frequency can be calculated by the formula for a half-wavelength resonator, allowing prediction of the resonances for the working frequency bandwidth of a specific application.

## V. Acknolwedgements

This work was supported partly by the National Science Foundation (NSF) under grant IIP-1916535.

## References

[1] E. -P. Li et al., "Progress Review of Electromagnetic Compatibility Analysis Technologies for Packages, Printed Circuit Boards, and Novel Interconnects," in *IEEE Trans. on Electromagnetic Compatibility*, vol. 52, no. 2, pp. 248-265, May 2010, doi: 10.1109/TEMC.2010.2048755

[2] Y. Wang, H. Wang and K. Wu, "Undesired Resonances in High-Speed Differential Pair due to Non-Ideal Return Path Design," *2019 IEEE International Symposium on Electromagnetic Compatibility, Signal & Power Integrity (EMC+SIPI),* 2019, pp. 316-320, doi: 10.1109/ISEMC.2019.8825288.

[3] Y. Liu, S. Bai, B. Pu, J. Lee and D. Kim, "Analysis on Unintentional Resonances in High-Speed Signals from Non-Ideal Routing Stub," *2021 IEEE International Joint EMC/SI/PI and EMC Europe Symposium,* 2021, pp. 994-999, doi: 10.1109/EMC/SI/PI/EMCEurope52599.2021.9559375.

[4] S. Bai et al., "Analysis of Power-via-Induced Quasi-Quarter-Wavelength Resonance to Reduce Crosstalk," *in IEEE Transactions on Signal and Power Integrity*, vol. 1, pp. 121-129, 2022.

[5] M. Makimoto and S. Yamashita, "Bandpass Filters Using Parallel Coupled Stripline Stepped Impedance Resonators," in IEEE Transactions on Microwave Theory and Techniques, vol. 28, no. 12, pp. 1413-1417, Dec. 1980, doi: 10.1109/TMTT.1980.1130258.

[6] S. B. Cohn, "Parallel-Coupled Transmission-Line-Resonator Filters," in IRE Transactions on Microwave Theory and Techniques, vol. 6, no. 2, pp. 223-231, April 1958, doi: 10.1109/TMTT.1958.1124542.