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Effects of Gapped Groundplanes and Guard Traces on Radiated EMI

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Abstract: Designers sometimes employ gapped reference planes to isolate analog and digital signals, and separate "quiet" and "noisy" ground structures by providing a series impedance. Guard traces are also used to reduce unwanted coupling to adjacent traces, which can lead to signal integrity or EMI problems. This study investigates the impact of gaps and guard traces on radiated EMI. A simple microstrip circuit was constructed to experimentally analyze the effects of groundplane gaps and guard traces.

I. INTRODUCTION

GAPS are sometimes cut in groundplanes to isolate analog and digital circuitry. The gap results in a series impedance between the two sections of the plane, with the objective of reducing noise currents between the regions and coupling to circuits referenced to the "quiet" ground. Signal currents that cross the gap return predominately along the path of least impedance. The increased impedance of the reference structure due to the gap in the plane can result in a current- driven noise source [1], which may drive EMI antennas comprised of extended reference structures.

Guard traces are typically grounded traces running parallel to a signal, and are often employed to minimize unwanted coupling to adjacent traces. They provide a degree of "shielding" and an alternate signal return path for capacitive or inductive parasitic currents that might otherwise be coupled to another signal trace and result in signal integrity or EMI problems.

Simple circuit models are used herein to review the principles of EMI noise sources. The concept of partial inductance plays a prominent role in defining one type of noise source. Groundplane gaps and guard traces affect the partial inductance of the reference structure, and therefore the radiated EMI. A simple microstrip geometry is constructed to experimentally evaluate the effect of groundplane gaps and guard traces on EMI. The length of the groundplane gap is varied and changes in common-mode current levels are measured using a swept-frequency two-port method. Similarly, two different guard trace configurations and various grounding techniques are investigated to study the effects of guard traces on EMI. A stripline configuration is also studied and proposed as a superior method of reducing EMI when compared to guard traces.

II. REVIEW OF NOISE SOURCE CONCEPTS

Groundplane gaps results in a larger inductance associated with the current path if a signal crosses the gap. The larger inductance is due to increased loop area in the current path. However, the change in inductance can be more intuitively related to EMI using the concepts of partial inductance and current-driven noise source mechanisms [1]. These concepts are briefly reviewed below for completeness.

Inductance may be defined as the flux that couples a closed path divided by the current conducted around that path. Although inductance is defined only for a closed path, the total inductance of a loop may be thought of as the sum of partial inductances associated with segments of the loop, where each partial inductance is defined as [2]

$$L_{partial_i} = \frac{\text{Total flux wrapping segment } i}{I_{loop}}. \quad (1)$$

The sum of the partial inductances associated with all the segments of the loop equals the total inductance. The total flux wrapping a straight conducting segment can be evaluated by integrating the flux penetrating a plane bounded by the conductor on one side and

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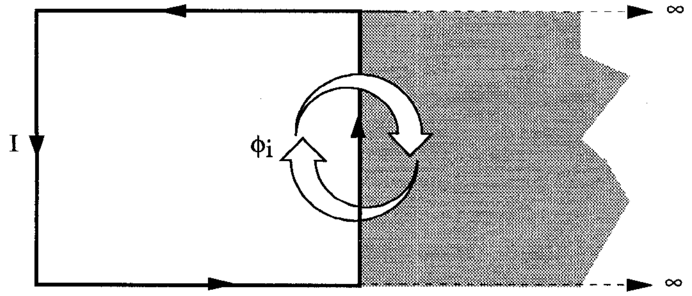

Figure 1. The total flux wrapping segment i equals the integral of the flux ϕ_i which penetrates the shaded "surface".

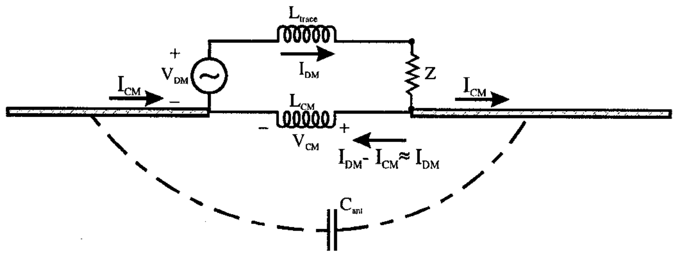

Figure 2. Schematic showing the physics of a current-driven noise source mechanism.

extending to infinity as shown in Figure 1.

The partial inductance of reference structures is the key to developing current-driven noise sources. Figure 2 shows a schematic of a current-driven noise source mechanism [1]. The differential mode current I_{DM} is conducted through the finite impedance return structure that is modeled schematically as an inductor. The resulting voltage drop V_{CM} drives the common-mode current I_{CM} through an EMI antenna. At low frequencies (well below the first EMI antenna resonance) the EMI antenna may be modeled as a capacitor. The EMI antenna, comprised of extended reference structures, is therefore modeled as a capacitor (C_{ant}) in Figure 2. An increase in the partial inductance of a PCB groundplane should cause a proportional increase in common-mode voltage, and consequently an increase in radiated EMI.

III. GAPPED GROUNDPLANES

Traces crossing gaps may impact signal integrity, because of the increase in the signal circuit inductance. However, in some lower speed designs, traces cross gaps with no adverse effects on signal integrity. Unfortunately, gapped groundplanes change the impedance of the reference structure, which may result in increased radiation even if the fundamental clock frequencies are low.

A. Theory

A groundplane of finite dimensions results in a finite impedance for return currents. For the simple microstrip configuration, where the trace is centered over the groundplane, the partial inductance is [3]

$$L^{plane}_{partial} \approx 4\frac{h}{w}(\frac{nH}{cm}). \qquad (2)$$

where h is the height of the trace above the groundplane, and w is the groundplane width. Equation 2 assumes that the height of the trace above the groundplane is much smaller than the distance from the trace to the edge of the groundplane. This criteria is not satisfied for a trace crossing a groundplane gap. However, when the trace crosses the gap, the groundplane is narrower and the signal current is farther from the return current. Therefore, the partial inductance of the reference structure is significantly increased.

Current takes the path of least impedance. Return currents will be conducted back to the source directly beneath the trace if the path is uninterrupted. The return current is conducted around the edge of the gap when the gap extends beyond the signal trace, as shown in Figure 3. The gap length is assumed electrically short, and the capacitive reactance of the gap is assumed large compared to the inductive reactance of the parallel path. The longer conduction current return path results in additional magnetic flux wrapping the groundplane. The partial inductance of the altered path increases as the gap length increases. An increase in the reference structure impedance results in an increase in common-mode current and EMI.

The differential-mode current will be negligible if the source or load impedance is large. The change in partial inductance should not significantly affect EMI in this case, because the dominant noise source is voltage-driven.

B. Experimental Results

A simple model consisting of a trace over a groundplane was constructed as shown in Figure 4 to study the increase in EMI resulting from a signal trace crossing a gap. A 0.085" semi-rigid coaxial cable was

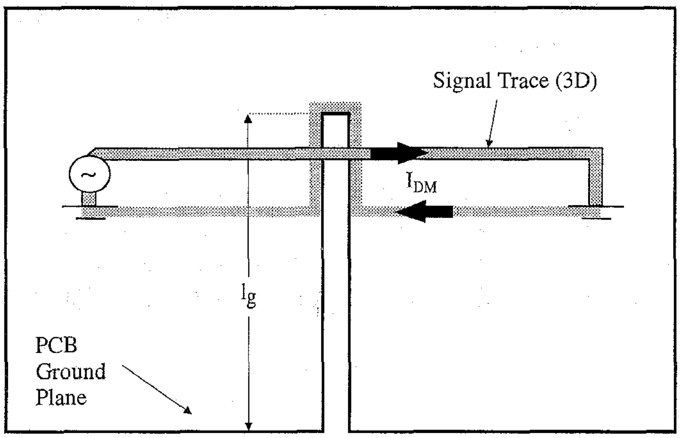

Figure 3. The signal current I_{DM} flows around the gap, generating flux which wraps the groundplane contributing to a larger partial inductance.

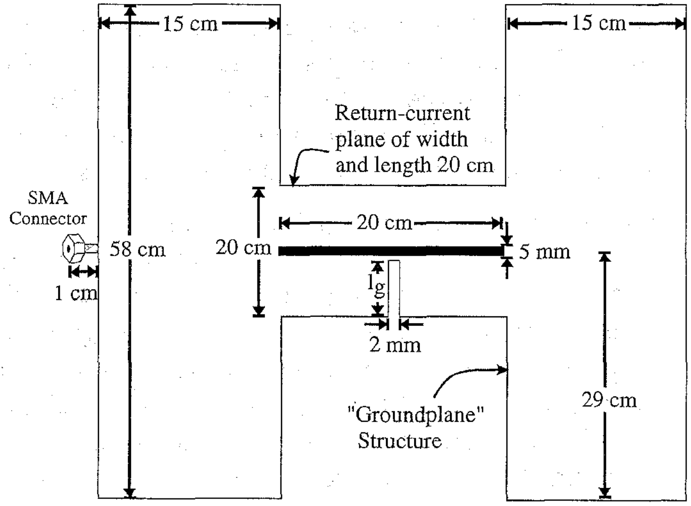

Figure 4. Model used to measure the effect of reference structure modifications on EMI.

well-grounded (outer conductor) with solder along its length to the large groundplane structure. One end of the cable was attached to a PCB mount SMA connector with its center conductor extending through the groundplane. The center conductor of the SMA connector was soldered to a 20 *cm* long, 0.5 *cm* wide 50 Ω microstrip transmission line. The other end of the microstrip was also connected to the center conductor of a PCB mount SMA connector, and the transmission line was terminated by attaching a load to the second surface-mounted SMA connector. The height of the microstrip above the groundplane was $h = 0.164$ *cm*, and the dielectric constant of the substrate was $\epsilon_R \approx 2.3$. An HP 8753C Network Analyzer was used to make two-port measurements. Port 1 was located at the coaxial cable SMA connector at the board edge. The common-mode current on the coaxial cable SMA connector shown in Figure 4 was measured at its connection to a 2' by 2' shield plate with a Fischer F-33-1 (200 kHz–250 MHz) clamp-on current probe connected to Port 2 of the network analyzer in a manner similar to that in reference [1]. The device-under-test (DUT) was connected through the shield plate test fixture to prevent coupling to the test apparatus, and ferrites were used on the current probe connector to prevent coupling to the probe. The calibration procedure removed the transfer impedance of the current probe from the measurement, so that

$$10log|S_{21}| = 20log\left[\frac{|V_2^-|}{|V_1^+|}\right] = 20log\left[\frac{100|I_{CM}|}{|V_S|}\right]. \quad (3)$$

The voltage V_1^+ is the incident wave from the network analyzer Port 1, and V_2^- is the transmitted wave to Port 2. The voltage V_S is the source voltage of the network analyzer.

The quantity of interest is the change in common-mode current I_{CM} as a function of the groundplane gap length l_g. To facilitate this measurement, the groundplane was extended in a "winged" fashion as shown in Figure 4 . This minimized artifacts such as flux coupling the coaxial cable and other measurement artifacts associated with the two trace endpoints.

A 2 *mm* wide gap of length l_g was cut in the groundplane. The PCB mount SMA connector was terminated in a short to create a current-driven noise source. Figure 5 shows the $|S_{21}|$ results for $l_g = 0$ *cm*, 5 *cm*, 9.5 *cm*, 10.5 *cm*, 13 *cm*, 19.5 *cm*, and 20 *cm* (no DC connection between the isolated groundplanes). The results for $l_g = 20$ *cm* show approximately a $20\frac{dB}{decade}$ increase in I_{CM} with frequency indicative of a voltage-driven noise source mechanism. The other gap length configurations show approximately a $40\frac{dB}{decade}$ slope, which is associated with a current-driven noise source mechanism [1]. Figure 6 shows the increase in $|S_{21}|$ as a function of l_g at 50 MHz relative to the 0 *cm* measurement. The common-mode current did not increase significantly when the gap did not extend beyond the trace conductor ($l_g \leq 9.5$ *cm*), with an average increase of approximately 3 dB when the gap extended to the edge of the trace ($l_g = 9.5$ *cm*). The common-mode current increased rapidly as the gap length increased beyond the trace with the largest

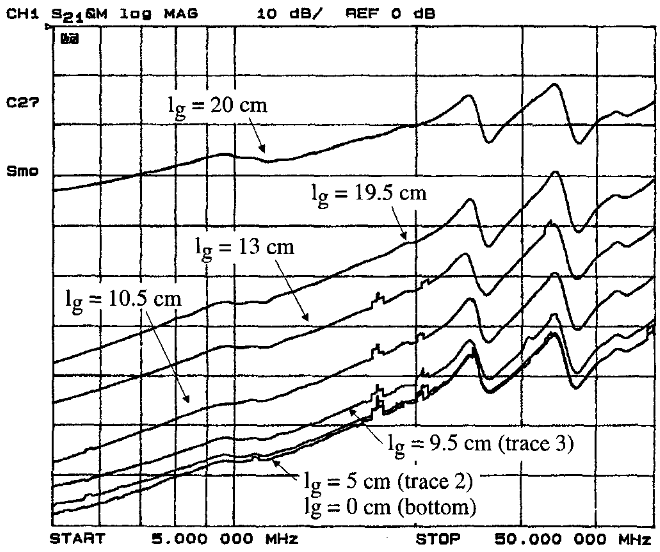

Figure 5. $|S_{21}|$ **results for a varying groundplane gap length** l_g **with a short-circuited microstrip.**

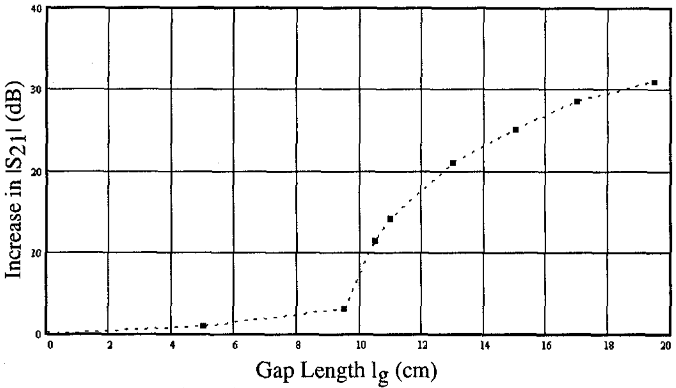

Figure 6. $|S_{21}|$ **increase as a function of** l_g.

increase approximately 31 dB ($l_g = 19.5\ cm$).

The small change in common-mode current for gaps of $0 \leq l_g \leq 9.5\ cm$ is consistent with the small change in groundplane partial inductance as the width of the conducting plane decreases. Using Equation 1, the per-unit-length partial inductance of the intact groundplane is approximately 0.033 $\frac{nH}{cm}$. If the width is cut in half, the per-unit-length partial inductance will double. Considering that the gap accounts for only 1% of the groundplane length, the change in partial inductance should be small if the gap is not cut under the trace or too close to the trace.

As the gap extends beyond the trace, the distance between the signal current and return current increases. The flux wrapping the reference plane due to the gap begins to dominate the impedance of the reference plane, resulting in significant increases in common-mode current. The uniform increase over the entire frequency range (5 MHz – 50 MHz) supports the current-driven EMI mechanism model using a partial inductance as the groundplane impedance.

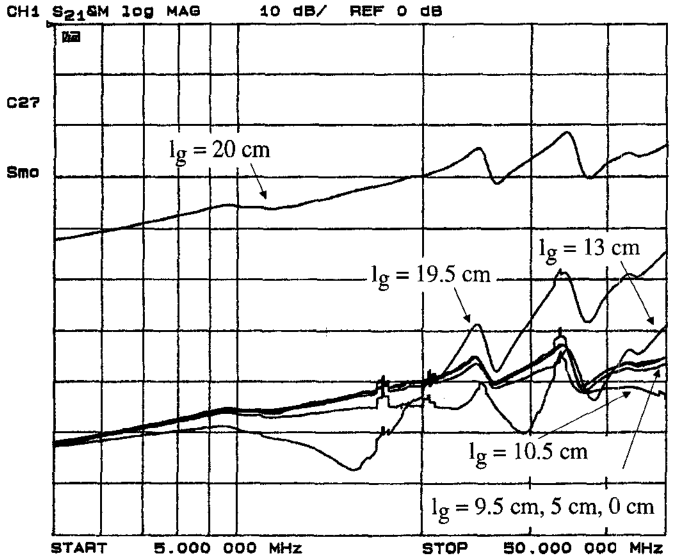

Figure 7. $|S_{21}|$ **results for a varying groundplane gap length** l_g **with an open-circuited microstrip.**

The measurements were repeated for an open-circuit load termination to explore the effect of the gap variation for the voltage-driven mechanism. The results are shown in Figure 7. There was virtually no change in common-mode current as the gap length changed at low frequencies, which is consistent with the voltage-driven EMI mechanism. At higher frequencies the reference structure exhibited various resonant changes as the gap length varied. These resonant changes may be due to the changing EMI antenna geometry as the gap length increases.

IV. GUARD TRACES

Guard traces adjacent to high-speed lines are often used to minimize coupling to other traces that may result in EMI problems; e.g., coupling to I/O lines, heat sinks, or "floating" conductors. Minimizing crosstalk for signal integrity is another motivation. The coupling is reduced through magnetic and electric field containment in proximity to the high-speed lines.

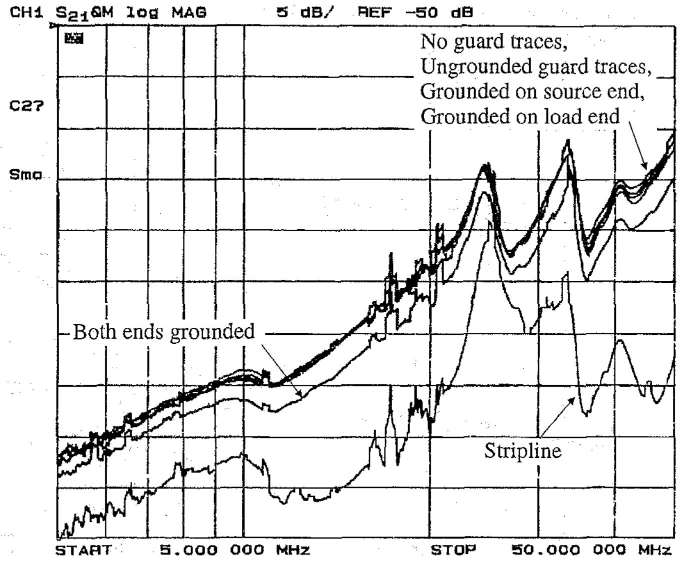

Figure 8. $|S_{21}|$ **results for various guard trace grounding configurations with a short-circuited trace.**

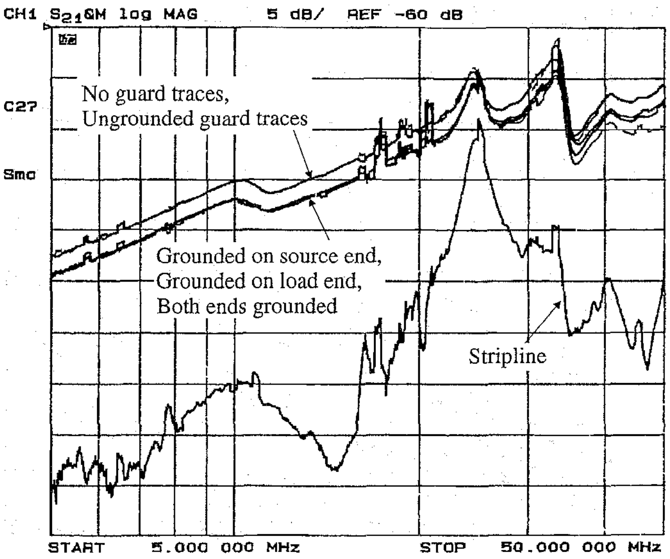

Figure 9. $|S_{21}|$ **results for various guard trace grounding configurations with an open-circuited trace.**

The DUT was modified to measure common-mode current changes due to guard traces with various grounding configurations. Only the effects on radiated EMI were studied. The guard traces were the same width and length as the signal trace and placed on opposite sides of the signal trace. The guard traces were grounded with 22 AWG copper wire pins on each end of each trace which passed through the dielectric and were soldered to the groundplane. The grounding pins were present for all grounding configurations, and non-grounded trace ends were folded back to prevent electrical contact. The swept-frequency common-mode current measurements were made with both grounded and ungrounded guard traces. Two spacing configurations were investigated with trace spacings of 1 *mm* and 2 *mm*. The 2 *mm* results showed little or no perceptible change in common-mode current regardless of the guard trace grounding configuration.

The results for the 1 *mm* spacing current-driven case with a short-circuited microstrip are shown in Figure 8. The common-mode current decreased on average by approximately 3.5 *dB* when both ends of the guard traces were grounded. The other grounding configurations showed no significant change in common-mode current from the case with no guard traces. The results are consistent with the partial inductance model. The current-driven mechanism results from magnetic flux that "wraps" around the groundplane. The guard traces contain the magnetic flux when they are well-grounded and therefore reduce the partial inductance of the reference structure. Conduction current does not readily flow on open-circuited guard traces. Therefore, the partial inductance is virtually unchanged unless both ends of the guard traces are shorted to ground.

The results for the 1 *mm* separation between the signal and guard traces with an open-circuited signal trace are shown in Figure 9. The common- mode current decreased by approximately 2.5 *dB* in all configurations where the guard traces were grounded in some fashion. In this case, the manner of guard trace grounding is less important since a change in reference structure partial inductance will not change the common-mode current when the mechanism is voltage-driven. The reduction in common-mode current in grounded configurations is because of electric field containment provided by the grounded guard traces.

Some reduction in EMI resulted with the guard traces. However, a stripline configuration should provide greater containment of the magnetic and electric fields associated with the high-speed trace. To demonstrate this principle, the DUT was modified to measure the common-mode current reduction with a stripline geometry. A second groundplane was constructed above the trace. The second plane was located 0.164 *cm* above the trace, and was separated from the trace by a dielectric with relative constant $\epsilon_R \approx 2.3$. The width of the second plane was the same as the return-current plane in Figure 4, while the length of the second groundplane was 21 *cm*. The second plane was centered above the trace. The ends of the secondary groundplane near the source and load of the trace were "stitched" to the primary groundplane with 15 pins constructed of 22 AWG copper wire. At each end, seven ground pins were spaced 0.5 *cm* apart symmetrically about the trace. The remaining eight pins were space evenly along the edge of the planes. No ground pins were located along the sides of the planes parallel to the trace. $|S_{21}|$ measurements were made and compared to the results of the guard trace experiments. The results for the short-circuited and open-circuited trace are shown in Figures 8 and 9, respectively.

The stripline geometry reduced the common-mode current by approximately 15 *dB* on average for the current-driven mechanism, and approximately 30 *dB* for the voltage-driven mechanism. This change is significantly greater than the 3.5 *dB* and 2.5 *dB* respective changes provided by the guard traces. This suggests that if a high-speed trace may be a contributor to radiated EMI by either a voltage- or current-driven mechanism, a stripline geometry is superior to guard traces. Furthermore, employing a stripline configuration may free valuable real-estate near PCB components.

V. SUMMARY

Circuit designers use gaps in groundplanes to isolate analog and digital circuitry by providing a series impedance between sections of the groundplane. However, gaps may cause significant increases in EMI radiation in designs where a signal trace crosses the gap, because of an increase in the partial inductance of the reference structure. The increased impedance of the reference structure may augment a current-driven EMI source, which may drive common-mode current on extended reference structures. Conversely, guard traces are employed to lower the impedance of the return current path, and provide isolation for high-speed lines that may couple to other devices. A simple microstrip geometry was constructed to experimentally study the changes in common-mode current resulting from groundplane modifications. Traces routed over groundplane gaps increase the partial inductance of the groundplane, and can lead to increase emissions. The experimental results supported this hypothesis, indicating that increased separation between signal and return currents results in increased radiated EMI. The EMI benefits of guard traces were also studied for both voltage- and current-driven mechanisms. Unfortunately, the experimental results indicate that the EMI benefits are minimal, though there might be signal integrity advantages. The common-mode current was reduced by approximately 3 *dB* when guard traces were placed 1 *mm* from a signal trace and grounded at both ends. Hypothetically, the EMI could have been further reduced by connecting the guard traces to the groundplane at multiple locations, but only a minimal improvement is expected. A stripline geometry was implemented experimentally and determined to yield superior performance in reducing EMI. The stripline geometry lowered the measured common-mode current on a cable by greater than 15 *dB* on average in this investigation. This suggests that the high-speed lines requiring electromagnetic isolation for EMI purposes should be routed as striplines, as opposed to employing guard traces.

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