90 Degree Corners:

The Final Turn

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Only a few topics generate the kind of enthusiastic discussion that a right angle corner on a trace does. Just the mention of 90^o corners --- regardless of whether you say that they shouldn't be used of if you say that they are harmless and can be used without concern--- guarantees a response from people with the opposite view.

Arguments against 90^o corners fall into two categories:

Impedance mismatch: A right angle corner is, necessarily, wider than the rest of the trace. This results in a decrease in Zo, the intrinsic impedance of the trace, and therefore causes an impedance mismatch at the corner. This, in turn, causes reflections, signal distortions, and noise along the trace.

I've even heard one speaker at a conference use the misguided analogy of electrons being like marbles; they will (he alleged) reflect back from a sharp 90^o corner but "bounce around" a 45^o one! (Honest, electrons don't act like that.)

EMI: The other argument against 90^o corners postulates that electronic fields become concentrated at the sharp corners, causing destructive electromagnetic radiation from that point that manifests itself as EMI. One author went so far as to say that "electrons virtually fly off the sharp corners of the bend." (Footnote 1.)

Some believers have used a toy "Slinky" to illustrate their position. The coils of the Slinky represent the circular magnetic field around the trace. The argument is that if you try to bend the Slinky into a truly sharp, 90^o turn, you can't do it. (Try it!) That, therefore, illustrates the sharp discontinuity in electromagnetic fields at such points, and makes it intuitively clear why EMI can (and does) become an issue.

The Test

Some people at the heart of the controversy decided to build a test board to actually control for and measure the effects that 90^o corners might have on traces. The benefits of this test would be to put to rest, once and for all, the arm waving that tends to go along with the arguments both sides offer. (Although, it might be worth pointing out that some think the arm waving is actually part of the fun!)

This type of experiment involves at least three types of resources that often don't exist at a single place. The test board needs to be conceptualized and designed; it needs to be fabricated; and then someone with the appropriate equipment and knowledge needs to do the testing and evaluation. See the *acknowledgment* at the end of this article for those who donated their time, effort, and resources for making this evaluation possible.

Figure 1 illustrates the board that was designed and fabricated. Six traces provided various configurations for test. All traces were configured as microstrip, controlled impedance traces with identical dimensions (1.2 oz copper, 10 mils wide with 7 mils FR4 dielectric thickness between trace and underlying plane, Er = 4.6). Provision was made at one end of each trace for a 50 Ohm RF connector for mating with test equipment, and for pads at the other end of each trace for impedance matching loads. All traces were precisely eight inches long. There were some other traces and connectors on the board (not shown) for additional investigations not related to this experiment.

Table 1 shows the corner configuration detail for each trace. Trace 2 was simply straight, with no corners, for control purposes. The others each had two identical bends ranging from a very sharp, 90^o turn (almost never actually seen on a board anymore) to a gently mitered 45^o corner. Trace 7 was an extreme configuration, a pair of sharp 135^o corners.

Results

Two types of analyses were performed on the traces, one for evaluating impedance discontinuities and the other for EMI radiation.

Impedance: First, each trace was examined using a TDR (Time Domain Reflectometer). This tool effectively measures the impedance at every point along the trace. **Figure 2** illustrates the geometry around a 90^o corner. The maximum width is 1.414 (square root of 2) times the nominal width. The theoretical effect this has on the characteristic impedance (Zo) of the trace varies (among other things,) with trace width, but is approximately a 15 to 20% decrease in Zo at that point (Footnote 2). The distance over which the effect is felt (theoretically) is equal to the trace width, W. Thus, the impedance (again theoretically) goes from nominal to about 20% below nominal in a distance of W/2 and then returns back to nominal in another W/2. For most traces, this is VERY quick.

Figure 3 illustrates a typical result of the TDR analysis. The rise time of the TDR pulse was approximately 17 ps, or approximately 110 mils along the microstrip trace, about 10 times the width of the trace. If there was a measured discontinuity along a trace, it was extremely small and limited to such a very short distance that the TDR could not resolve it with a 17 ps pulse rise time.

In summary, the effect of 90^o corners on Zo are small and hard to measure and are much less than the effects of simple vias. (Footnote 3)

EMI: Although testing for EMI emissions is difficult under any conditions, the situation is a little easier here. In this case we are not interested in the *absolute* magnitude of the emissions from the traces --- just the *relative* level of emissions between the various corner configurations. The question is not what the level of emissions is, the question is whether 90^o corners radiate worse than mitered or 45^o corners.

A test was set up as shown in **Figure 4**. The board was driven by port 1 of a network analyzer while radiation from the board was "received" by a log periodic antenna placed approximately one meter away. The measurements were taken in a partially shielded room. Over 60 radiation measurements in all were made involving various traces, horizontal or vertical orientation of the circuit board, and loaded or open circuit trace conditions, etc.

A baseline measurement was taken by simply extending the center conductor of a shielded cable 3 cm, allowing it to act as a small monopole antenna. Radiation measurements were taken from this small reference antenna up to about 1.3 GHz.

Then the Network analyzer was used to measure the forward transmission coefficient, S21, between ports 1 and 2. This was used as a normalized measure of radiated field strength. The network analyzer was first not connected to any trace (establishing an experimental noise floor) and then to trace T2. The radiated emissions from the straight trace were approximately 15 dB above the noise floor, but at least 35 dB below the emissions from the short reference antenna.

Then the remaining traces were evaluated for radiated emissions. Traces 3 (90^o corners) and 6 (45^o corners) both radiated slightly higher than did Trace 2 (no corners). Trace 6 actually radiated slightly higher than did Trace 3, contrary to any expectation. But none of the traces radiated at a level judged to be significantly higher than any other trace. This illustrates two things: (a) the difficulty of taking these kinds of measurements, and (b) the fact that the effects of the corners (if *any*) are significantly less than other measurement errors that exist in this kind of analysis.

Conclusions:

The TDR data do not show any measurable reflections from either 45^o or 90^o corners in microstrip traces. In theory, there is a change in Zo caused by a corner, but the effect is not sufficient to be resolvable with a 17 ps rise-time pulse.

The radiated emission measurements (up to 1.3 GHz.) do not show an increase for 90^o corners, compared to 45^o corners, that is larger than measurement uncertainty. All of the trace geometries measured produced radiated emissions that were 35-50 dB below the emissions of a 3-cm long monopole antenna and only slightly above those from a straight trace with no corners.

For most circuit boards it is expected that discontinuities encountered at IC packages, connectors, and vias will produce much larger reflection or radiation effects than *either* 45^o or 90^o corners.

Footnotes

1 This led to a discussion of "electron grabbers" suitable for catching and using such "flying" electrons. See "Backpage", February, 1996

2. For the formulas for calculating impedance, see "Brookspeak:Controlling Impedance", Jan. 1997

3. See, for comparison, "The Effects of Vias on PCB Traces", August, 1996.

Acknowledgment. This study presents a model of industry cooperation for the common goal of increasing understanding. The board design was contributed by UltraCAD Design, Inc. (Bellevue, WA.) The test boards were fabricated and donated by Omni Graphics Ltd. (Richmond, BC. Canada). The test equipment and measurement resources were donated by Drs. Tom Van Doren, Todd Hubing, and Sergiu Radu, Electromagnetic Compatibility Lab, Univ. of Missouri-Rolla. None of these partners had all of the resources required to do this study on their own. Their mutual cooperation made this effort possible.

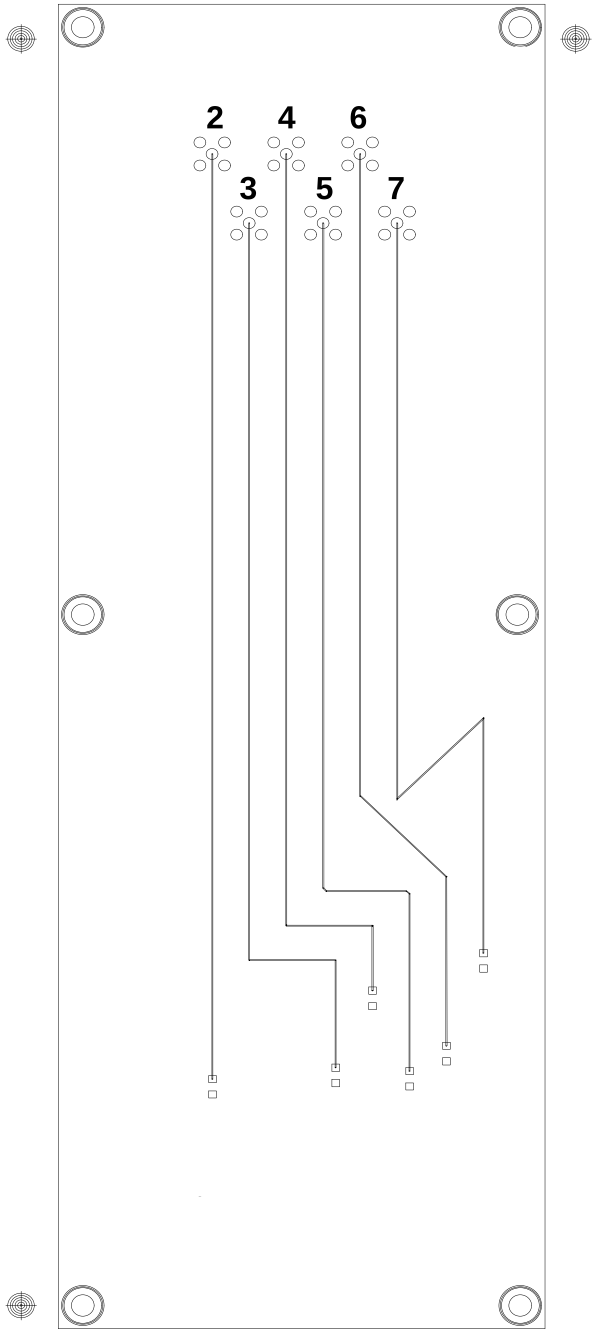
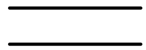
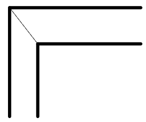
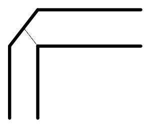
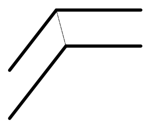
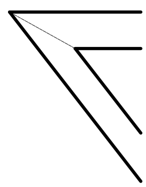


Figure 1
Test Board and Traces.

Table 1
Trace Corner Configurations

Trace #	Configuration	Max. Width At Corner
2		na
3		W * 1.414
4		W * .707
5, 6		W * 1.082
7		W * 2.613

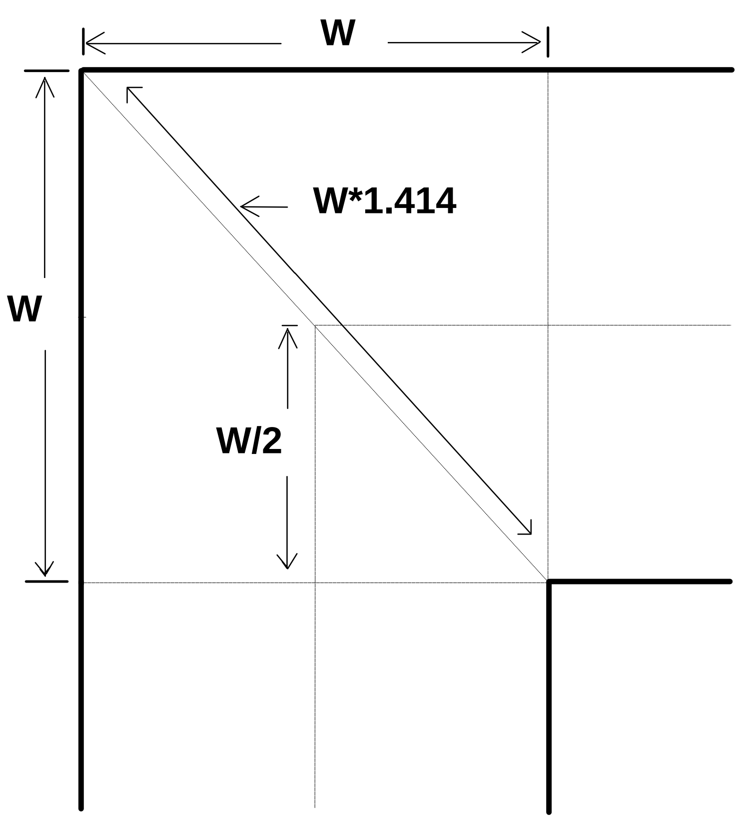


Figure 2
Geometry of a 90 degree corner

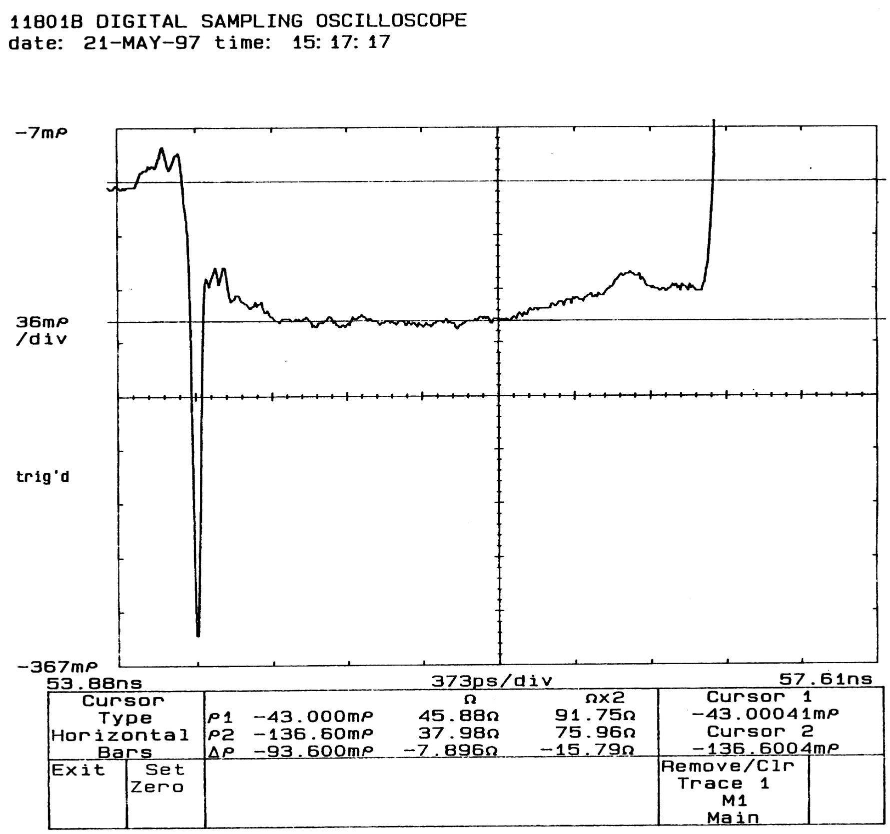


Figure 3
Typical TDR Output, Trace 3

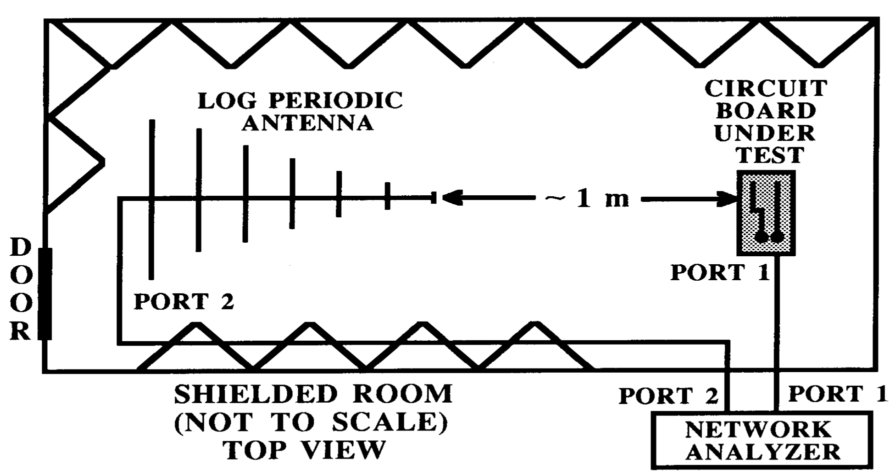


Figure 4
EMI Test Lab Setup