A Review of 90 Degree Corner Design for High-Speed Digital and mmWave Applications

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***Abstract*—The design of 90 degree corners has been an important topic since the start of microwave design several decades ago. With the arrival of standards like 400Gb Ethernet, 5G and WiGig, engineers are now required to create PCB designs with signals in the mmWave frequency range for consumer applications. In this paper we will do a quick review on the design of right angle corners for PCB construction and present some measurement results.**

Keywords— Microstrip routing, Right Angle Corners, mmWave.

I. Introduction

There was a time where discussing the impact of right angle corners in printed circuit board (PCB) signal traces was restricted to engineers working in niche applications. This is no longer true with some mainstream applications in both RF and digital applications already in the mmWave frequency range. For the benefit of engineers starting to work on these applications without past experience with right angle corners at mmWave frequencies, we present in this paper a review of the key points of designing right angle corners in printed circuit board signal traces. We also present some measured results up to 65 GHz from manufactured test structures using de-embedding techniques to remove the impact of the connector transition.

II. Right Angle corner design

To the best of our knowledge, the first studies on microstrip bends are almost 50 years old [1]. The topic was well established in the following 20 years [2-6]. The quintessence, of all that research effort could be condensed in Figure 1. Figure 1a shows the physical structure of a microstrip mitered bend (dash triangle), two short feeding microstrips (gray rectangles) have been added, in order to show how the bend is connected with the rest. The relevant geometrical parameter of the structure is the so-called miter ratio (or miter factor) $M=d/\sqrt{w}$: M=0 means a square bend, M=0.5 means an isosceles triangle (half of a square). A relatively good approximated equivalent circuit is shown in Figure 1b. The two transmission lines (with identical parameters) TL1,TL3 have the same characteristic impedance as the feeding lines (gray rectangles in Figure 1a, i.e. microstrips with width w); they produce a phase shift on the S-parameters. The two inductors L1, L3 (both with the same inductance L_1=L_3) together with the capacitor C2 (with capacitance C_2) play the main role in the bend's modeling. Intuitively, it can be seen that the higher the M, the higher L_1=L_3, the lower C_2, and vice-versa. If M is made such that $Z_0 = \sqrt{2 \cdot L_1 / C_2}$, where Z_0 is the characteristic impedance of the feeding lines, then the bend is "seamless" or well matched, that condition usually happens with M close to 0.5. The true optimum value depends on the substrate and on the frequency range. It has to be remarked that the electrical length of a bend could be longer, equal, or even shorter than that of a straight section of microstrip with the same width and length, depending on w, substrate height h and dielectric constant ε_r, and metal thickness t.

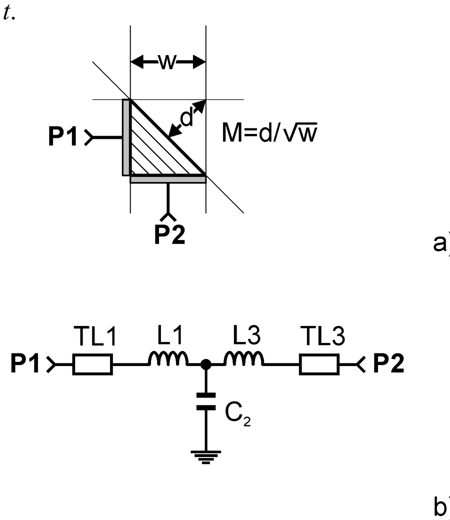

Figure 1: Microstrip bend: a) physical structure, b) equivalent circuit test.

In order to keep the investigation less abstract, one practical example was considered, using a substrate with h=200 µm, ε_r=4, t=30 µm and a corresponding 50 Ω microstrip width of w=397.5 µm. Figure 2 shows three possible bends with different miter ratios, all of them having a 400 µm long 50 Ω microstrip line on both sides. Figure 3 shows the resulting amplitude of reflection (right-y) and transmission (left-y) coefficients. It can be seen that M=0.5 is close to the "optimum", while M=0.4 (closer to a full square bend) is the worst case among the three considered.

However, if the frequency range of interest is below 11.8 GHz (where the blue line crosses the green one), the lowest reflection coefficient amplitude is given by M=0.6, not M=0.5. The general conclusion that could be taken from this example is that a true "optimally mitered" bend configuration of general validity simply does not exist, although commercially available RF circuit simulators offer such element. The situation could be even more complicated if real components - instead of perfectly matched 50 Ω S-parameter ports - are connected with the RF ports P1, P2. Real components are never perfectly matched, therefore, the discontinuity due to the bend interacts with the standing wave regime caused by the non-ideal termination. Consequently, the optimum M can further change.

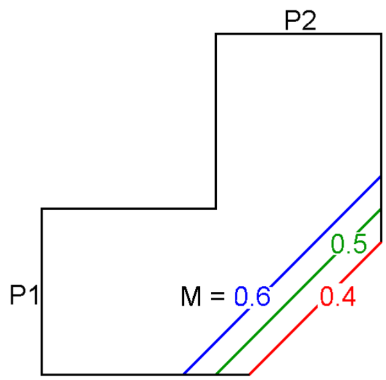

Figure 2: Some microstrip bends with different miter factor.

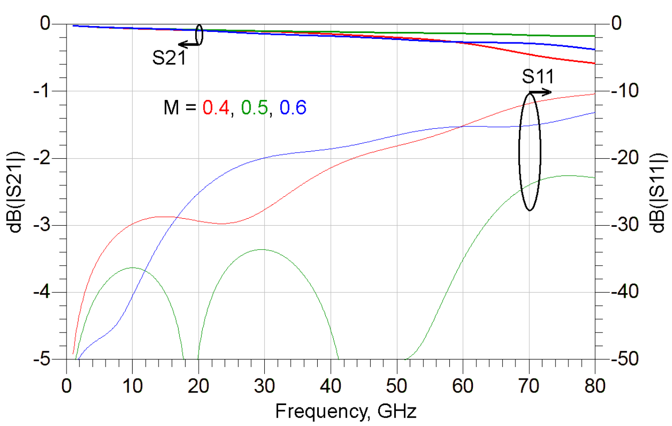

Figure 3: Transmission and reflection coefficients of the bends represented in Figure 2.

One more aspect to consider is the old, and never well answered, question: Is it better to use a smooth curved right angle bend or an abrupt square/miter bend? Again, in order to consider a practical example (still with the same substrate and 50 Ω line as per Figure 2 and Figure 3), let us consider the layouts shown in Figure 4, where the distance between the RF ports P1, P2 is (x=4.4 mm; y=0.9 mm). Three of the many possibilities are shown in Figure 4: 90° bends (blue), 60° round curves (red), 30° curves (green), the corresponding amplitudes of reflection (right-y) and transmission coefficient (left-y) are shown in Figure 5. It can be seen that there is no dramatic difference among the three cases. Moreover, the theoretical worst case could be the best one in practice, due to inaccuracies of the realization process, limited precision of the simulation models, termination impedances different from the ideal 50 Ω case.

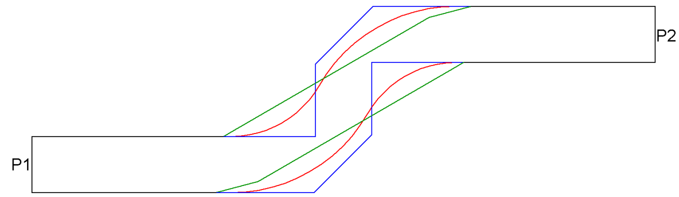

Figure 4: Three possible routings for two offset lines: with 90° bends (blue), 60° round curves (red), 30° bends (green).

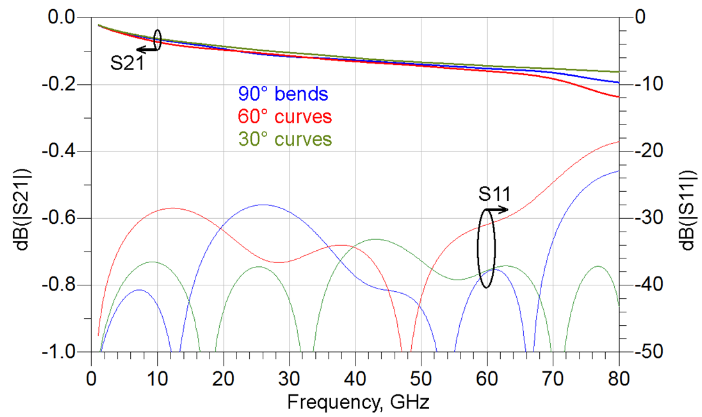

Figure 5: Transmission and reflection coefficients of the RF paths represented in Figure 4.

III. MEASUREMENT EXAMPLE

To demonstrate the impact of the right corner design, the PCB test coupons shown in Figure 6 were manufactured in Rogers 4350B using a 0.5207 mm wide microstrip (20.5 mil) in a 0.254 mm thick dielectric (10 mil). The microstrip traces used a NiAu plating without any soldermask. The connectors are 1.85 mm type from Signal Microwave (ELF67-002) with a custom optimized footprint for the used stackup.

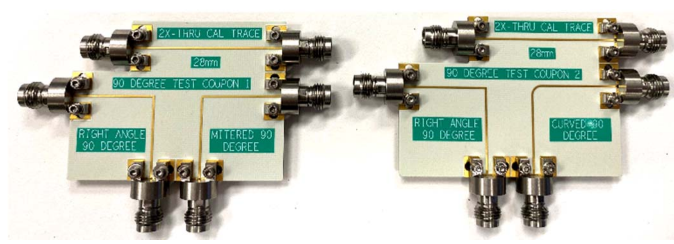

Figure 6: Manufactured PCB test coupons including a straight right angle, a mitered right angle and a curved right angle. Also included in each PCB coupon is a connector de-embedding structure.

To be able to measure and compare the different right angle designs at mmWave frequencies (in this paper up to 65 GHz), it is not only required to have an excellent connector to PCB microstrip transition but also to de-embed the impact of the connector transition. For this the test coupons also include a 28 mm length 2x-thru de-embedding structure so that we can de-embed the connector and its transition plus part of the microstrip trace [7,8]. Figure 7 shows the measured insertion and return loss of the 2x-thru structure where one can observe better than 10 dB return loss up to 65 GHz and also a separation greater than 5 dB between the insertion and return loss. As discussed in [7], this demonstrates that not only that we have an excellent connector transition but also that this 2x-thru structure can be used for de-embedding up to 65 GHz.

The mitered right angle test structure used an M values of 0.5 and the curved right angle used a radius of 2.5 mm. Figure 8 shows pictures of the manufactured right angle structures. As can be observed, PCB manufactured structures are never perfect, a straight angle right corner will have slightly round edges depending on the etching process.

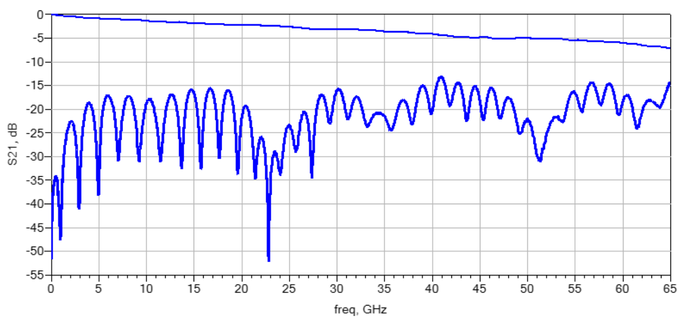

Figure 7: Measured insertion and return loss of the 28 mm 2x-thru de-embedding structure.

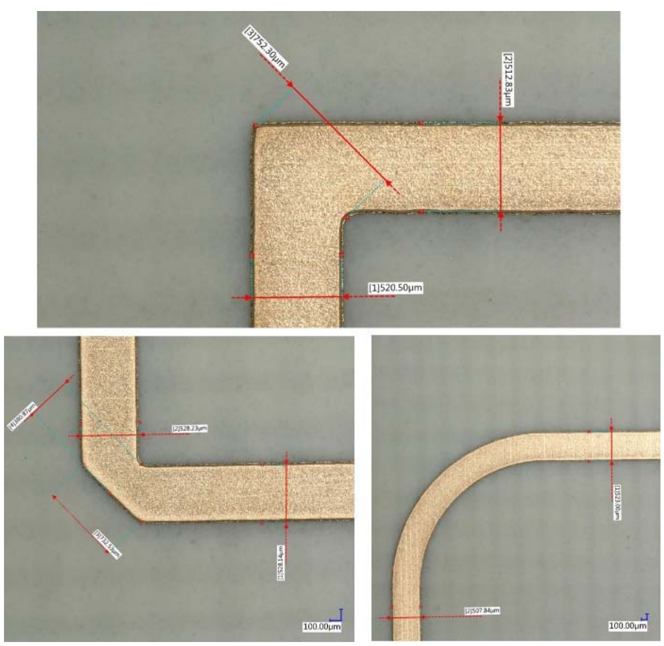

Figure 8: Pictures of the manufactured right angle structures.

Figure 9 presents the measured insertion and return loss results after connector de-embedding for each structure. De-embedding was preformed using the Keysight PLTS 2020 software package and after de-embedding only a 1 mm microstrip trace is present before the right angle structure. The results clearly show the performance advantages of both the mitered right angle and also the curved right angle compared with the straight right angle. Note that the curved right angle PCB structure is longer than the mitered right angle structured which also implies it is slightly more lossy. The measurements were performed with harmonic sampling from 6.5 MHz to 65 GHz (10.000 points) and an IF bandwidth of 1 kHz.

IV. Conclusions

This paper has presented a review of the design of right angle corners and showed some measurement examples. In conclusion both mitered and curved right angles showed improvements compared with a straight right angle and similar performances. This paper again stresses the point that square right angles do have bad performance at mmWave frequencies and should be avoided. It is also important to understand that right angle design discontinuities can impact EMI [9] or even DC [10].

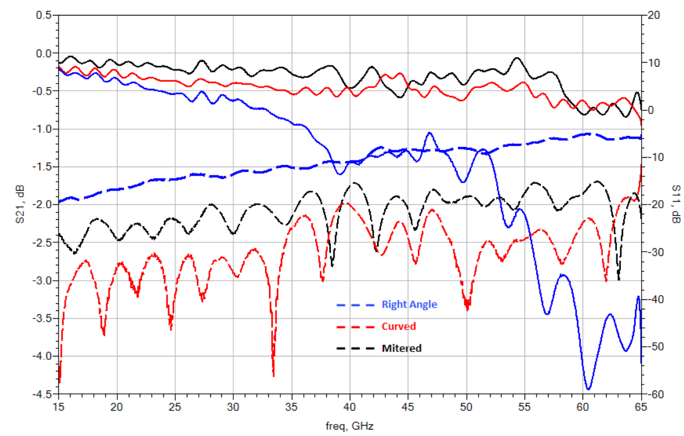

Figure 9: Measured insertion and return loss after connector/signal trace de-embedding.

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