Validation of Bend Models with Measurements

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Bends in PCB traces look like very basic and simple structures and easy to simulate. Technically, one can do the analysis with any electromagnetic solver with sufficiently accurate port de-embedding capabilities, as it was demonstrated with Simbeor software in [1]. The reflections from a bend in digital interconnects are relatively small and may be not even detectable with the measurements. So, who cares? Surprisingly, my recent post on how to minimize the reflections from the bends at LinkedIn generated a lot of interest and questions https://www.linkedin.com/pulse/how-interconnects-work-minimal-reflection-90-degree-bends-shlepnev The bend effect may be negligible in narrow digital interconnects, but not so in wider traces used in RF/Microwave structures that nowadays are often implemented on PCBs. Obviously, more work on bends is done in that area. Jose Moreira pointed out at one of the recent publications on the bend optimization and validation [2]. He also suggested correlating the measurements done at Advantest with the analysis in Simbeor and provided all necessary measured data for structures shown in Fig. 1 – excellent opportunity to validate electromagnetics with measurements (or the other way around☺). So, here is the outline of all the validation steps and the results.

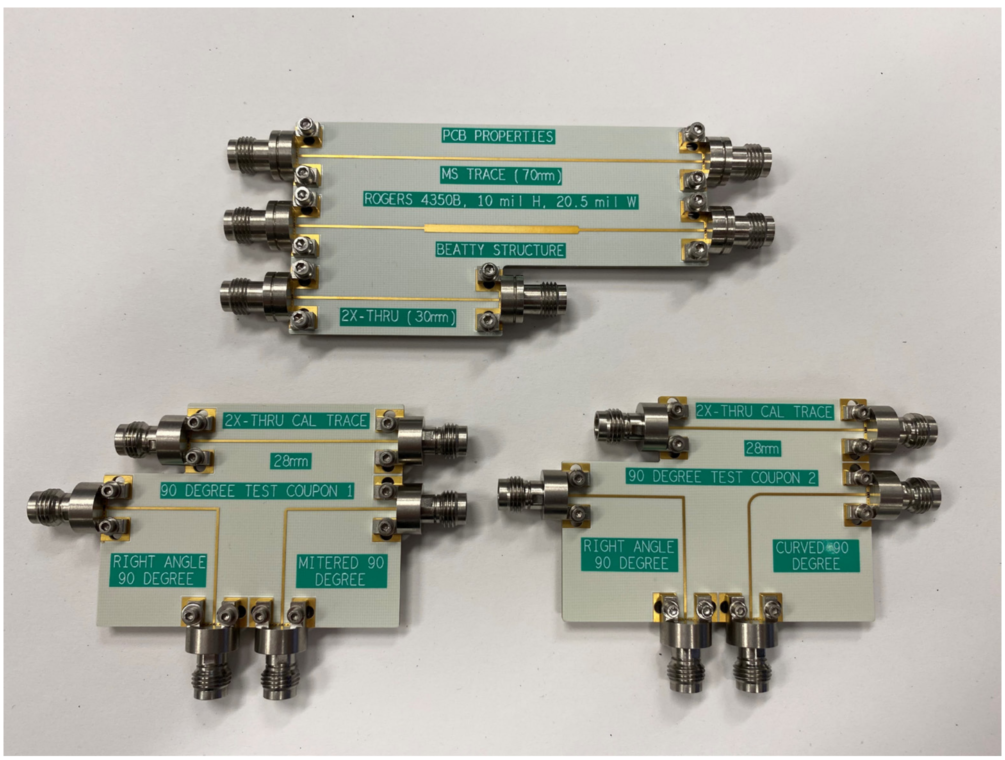

Fig. 1. Test structures from Advantest for material model identification (top) with uncompensated and mitered bends (bottom left) and uncompensated and curved bends (bottom right).

The first step is to identify the material properties. The results usually do not correlate well without the identification step. The material identification can be done using S-parameter measurements for long and short lines (top structure in Fig. 1) with the reflection-less GMS-parameters [3] in Simbeor software. S-parameters are measured up to 60 GHz and provided by Jose Moreira from Advantest. All quality metrics of measured S-parameters came out as good or acceptable and TDRs of two line segments were consistent for the material model identification up to 60 GHz. All test structures are microstrip lines plated with thick layers of nickel (assumed as typical 6 um) and relatively thick layer of gold (assumed 0.1 um – thicker than usual). That plating is important to account in the model - it produces substantial effect on the losses. We know properties of Rogers 4350B dielectric from manufacturer (may be a starting point in the material identification) and can take Landau-Lifshits model for nickel from [4]. The unknown here is mostly the roughness model parameters. The outcome of the identification is the models with parameters shown in Fig. 2 – that produces correlation in GMS-parameters shown in Fig. 3. To capture the high-frequency dispersion Simbeor 3DML solver was used for all simulations in this paper.

Fig. 2. Material models and stackup. Roughness is specified for rough surfaces of copper in stackup as Huray-Bracken model with SR=0.6um and RF=8.

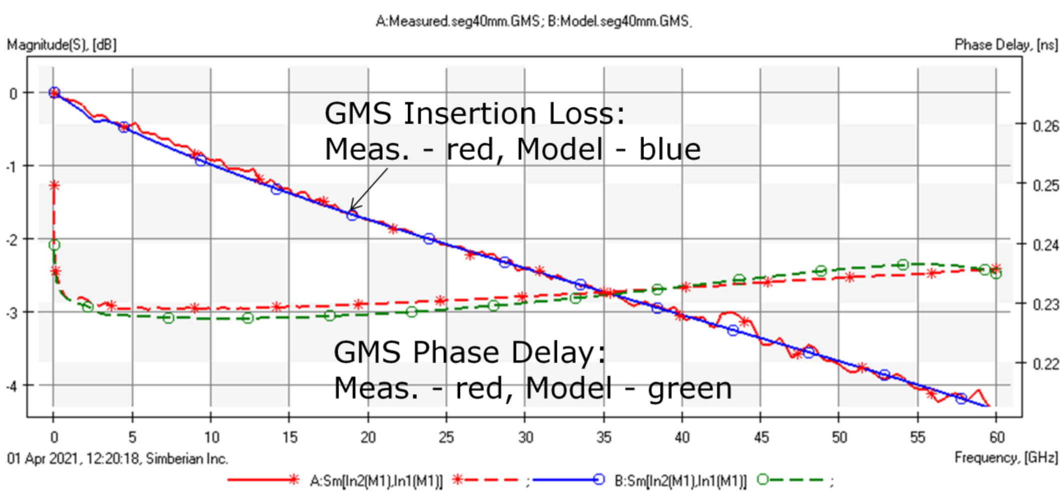

Fig. 3. Measured and modeled reflection-less GMS transmission parameter for 20.5 mil wide, 40 mm segment of plated microstrip line (difference of long and short line) after adjustments of the material models.

S-parameters of line segments and cross-section of trace can be also used in Simbeor for de-embedding with ETF method and used here to de-embed the Beatty standard resonator (structure with wider line in the middle in Fig. 1) for validation of the material models. Fig. 4 shows almost excellent correlation up to about 45 GHz. Correlation at higher frequencies breaks due to the geometry variations on real structure (shows up as the differences in measured |S11| and |S22|) as well as high-order modes in the model.

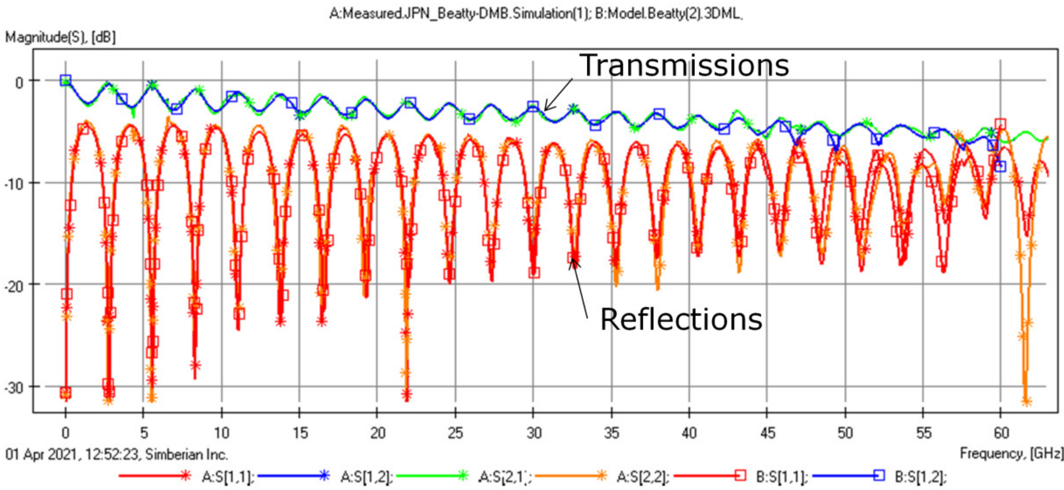

Fig. 4. Identified material model validation with measured and de-embedded S-parameters of Beatty standard – collocation of the resonances demonstrates proper dispersion modeling.

The next step is to create models of the bends and correlate with the measurements. TDR computed from measured S-parameters of the bends is shown in Fig. 5 (computed with RCM in Simbeor). The effect of the bends is quite visible here due to the wider than usual traces.

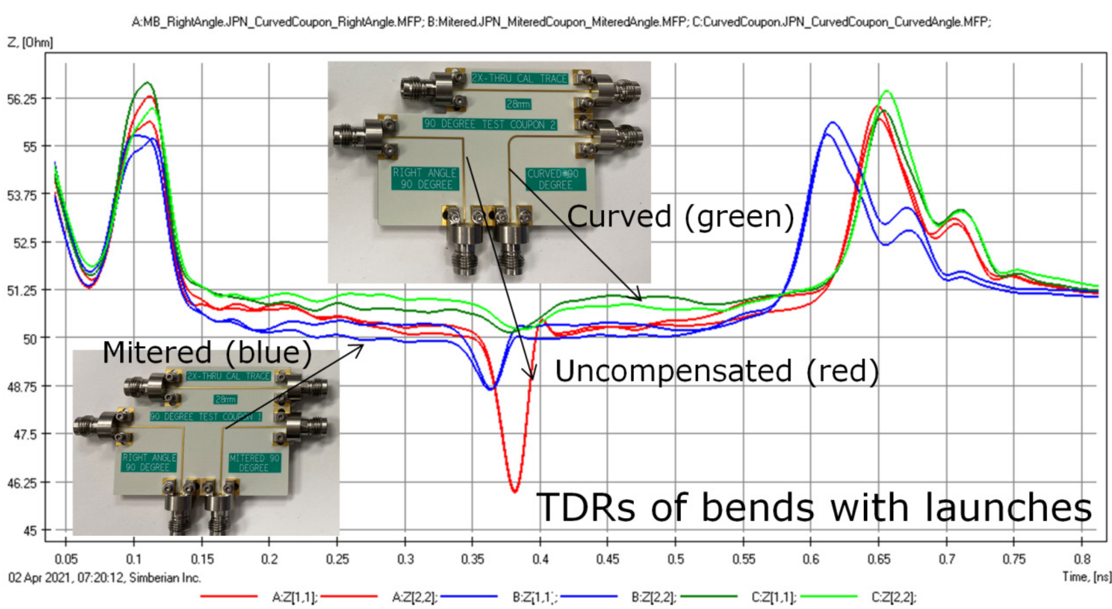

Fig. 5. TDRs computed from measured S-parameters for three test structures from the opposite ends.

The uncompensated bend has almost 4 Ohm dip (red lines), mitered bend has a little over 1 Ohm dip (blue lines), and curved one has less than 0.5 Ohm dip (green lines). The bend dips are in the middle of TDR graphs. All bends add capacitance. We can also observe that the real structures have substantial manufacturing variations – about 1 Ohm along the traces and about 1.5 Ohm in the launches – this is important to notice. There are 2 ways to proceed with the model building and comparisons. First way is to create models for the whole structures, including the connectors and launches. Possible, but requires geometry or models of the connectors and more complicated to setup.

Another option is to de-embed the connectors and launches and have measured S-parameters for just the bends with small segments of traces on both sides. De-embedding is a way to subtract the effect of connector, launch and some trace segment from the original S-parameters – that leaves S-parameters only for the structure under investigation (bends in this case). Identified S-parameters of half of the 2x through structure can be used for such subtraction. That is what was done in [2] with AFR de-embedding method (see details in the paper) and Jose Moreira provided measured and de-embedded S-parameters as well. Geometry of each bend imported into Simbeor software from ODB++ file together with materials and stackup data from the material identification project (Fig. 2). Discontinuity selectors created for each bend, to have phase reference planes exactly at the de-embedding plane. Interpolative sweeps used for all computations – it simultaneously builds rational compact model, that allows direct computation of TDRs for each bend. The de-embedding in [2] was done with the 2x through structure – half of the length of this structure gives the location of the de-embedding planes. Simulation of the bends is really simple to do and here is the moment of truth – the analysis to measurements comparisons of TDR and S-parameters are shown in Fig.6 – Fig. 11.

Well, how good is that? It depends on how you look at it. Overall we can conclude that the correlation is good for uncompensated and mitered bends with higher reflections (Fig. 6 – Fig.9). Correlation of reflection parameter for the curved bend is not so good and the reason for that is the problem with de-embedding. After all, if experiment does not correlate with the theory, blame the experiment☺. Notice that all de-embedded S-parameters have some oscillations in both magnitudes and phases and computed S-parameters are smooth. Is this a problem with the modeling or measurements? Are those oscillations physical? In this case it is the problem with de-embedding due to geometry or material properties variations in the test fixtures. The variations in the launches and traces are clearly visible on TDRs in Fig. 5 as well as in Fig. 12. When S-parameters of the 2x through structure are divided into S-parameters of two halves, those halves are not exactly the same as the transitions to be removed in the structures with the bends. Thus, when subtraction is done, the differences show up as the ripples. Though, such S-parameters have acceptable quality and can be easily converted into passive and causal rational compact macro-models as it is done here for the TDR computations for uncompensated and mitered bends. It was not possible to reasonably fix S-parameters for curved bend with the reflections below -20 dB – the noise introduced by physical differences in test fixtures was comparable with the effect of discontinuity in this case.

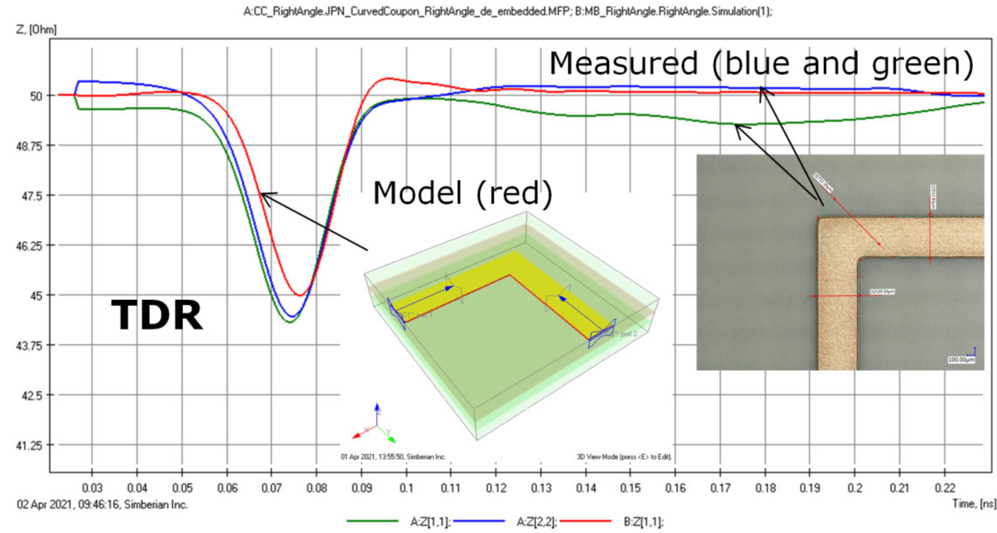

Fig. 6. TDR computed from measured and de-embedded S-parameters and from modeled S-parameters of uncompensated bend.

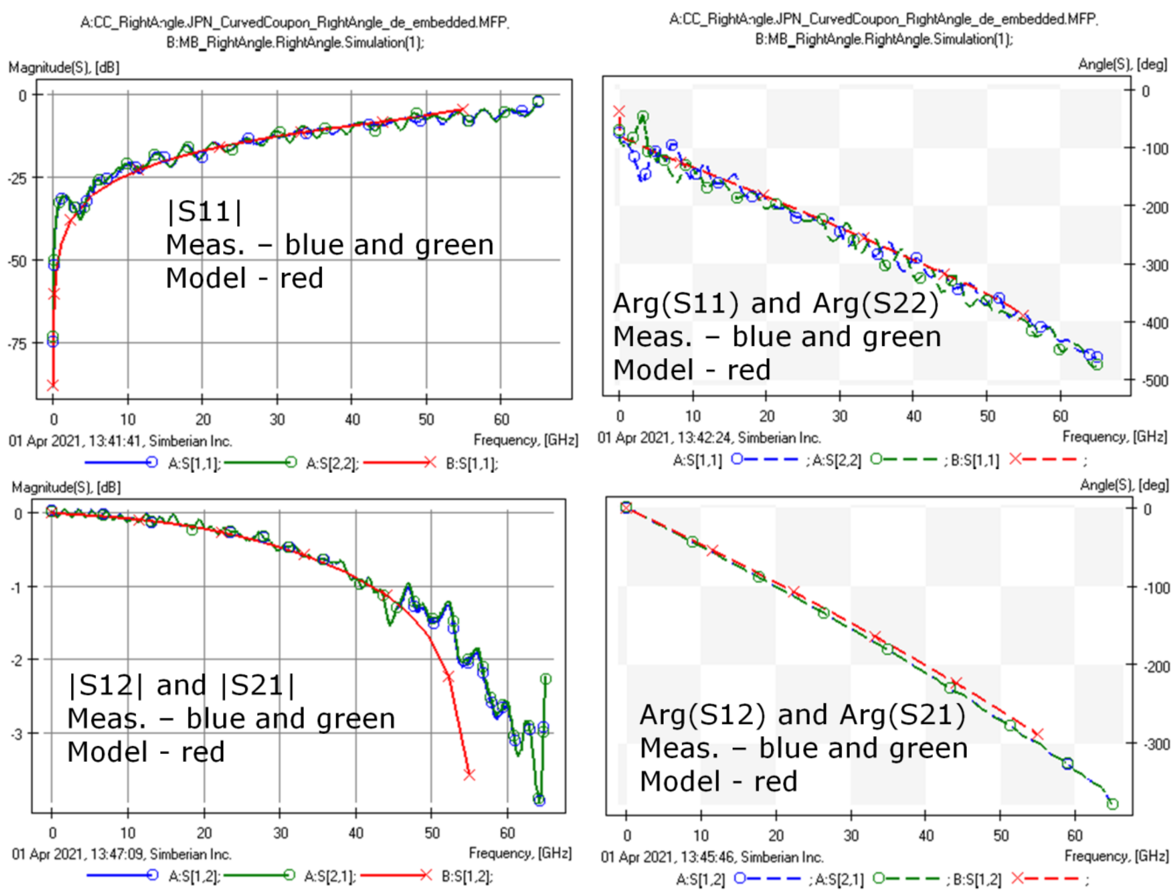

Fig. 7. Magnitudes and angles of measured and modeled S-parameters of uncompensated bend.

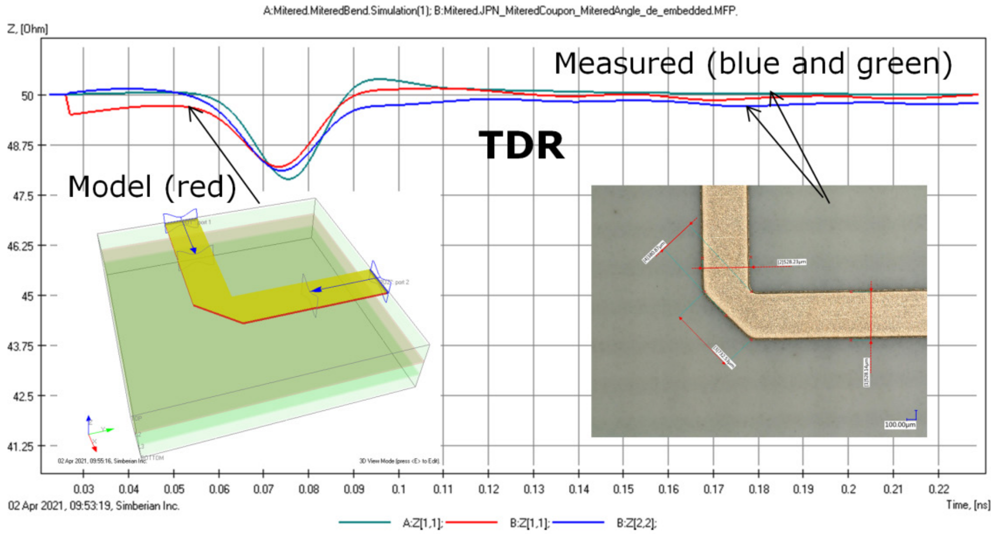

Fig. 8. TDR computed from measured and de-embedded S-parameters and from modeled S-parameters of mitered bend.

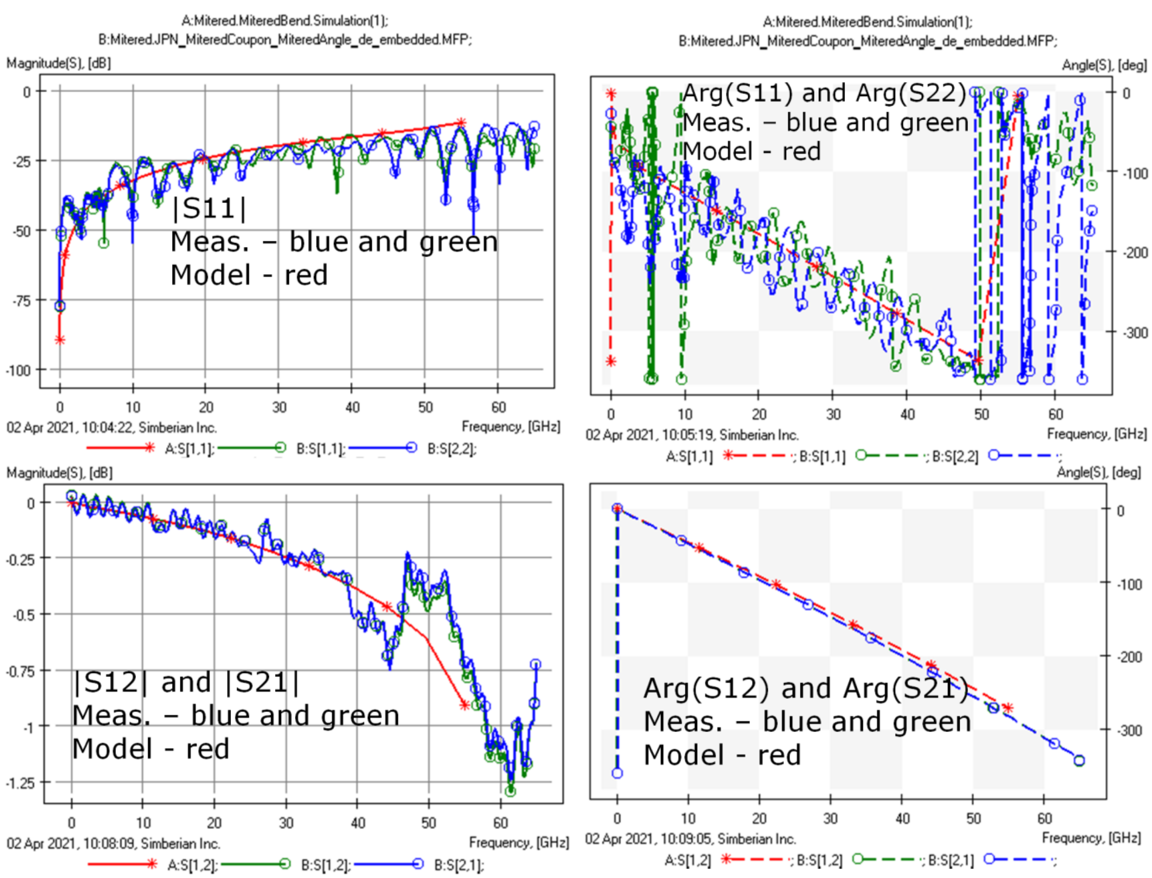

Fig. 9. Magnitudes and angles of measured and modeled S-parameters of mitered bend.

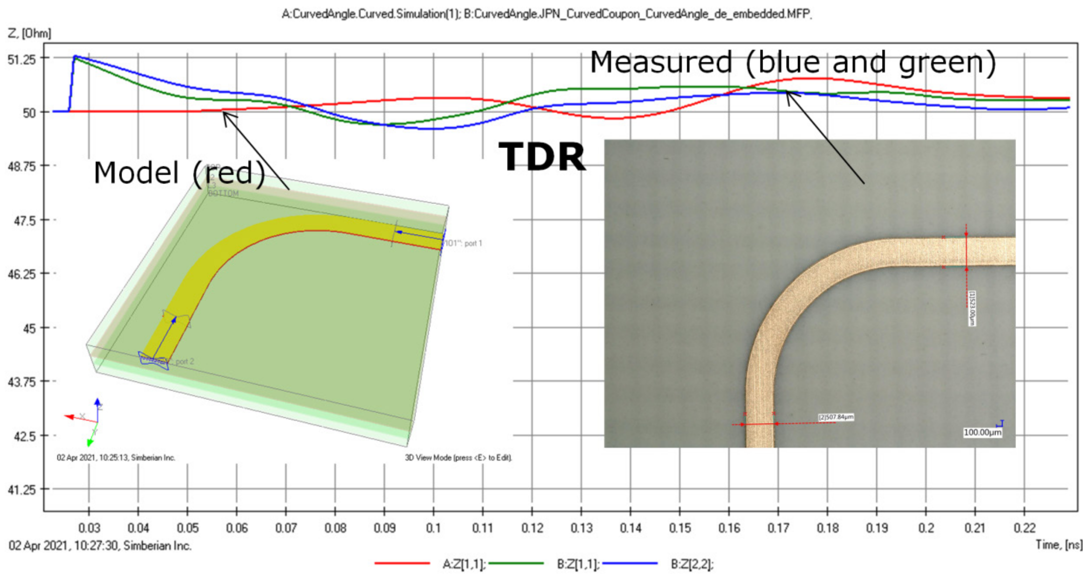

Fig. 10. TDR computed from measured and de-embedded S-parameters and from modeled S-parameters of curved bend.

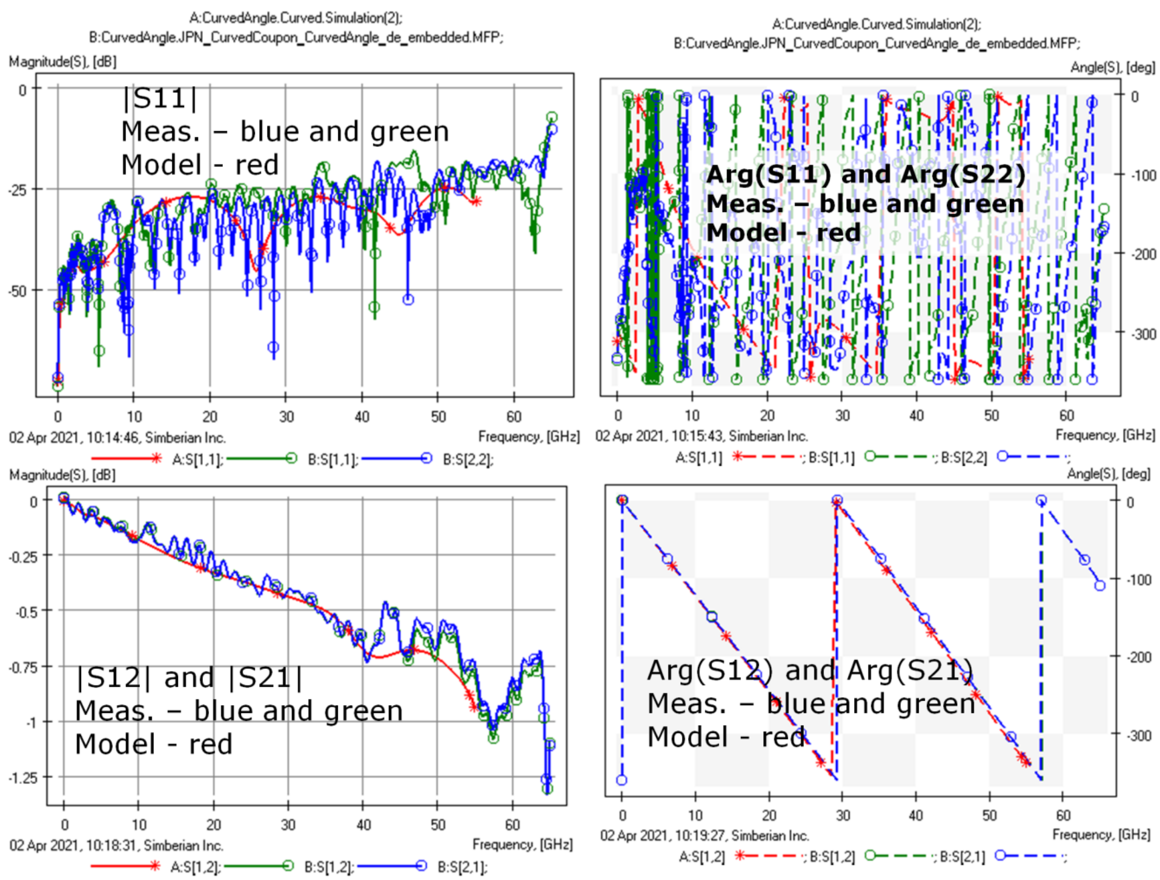

Fig. 11. Magnitudes and angles of measured and modeled S-parameters of curved bend.

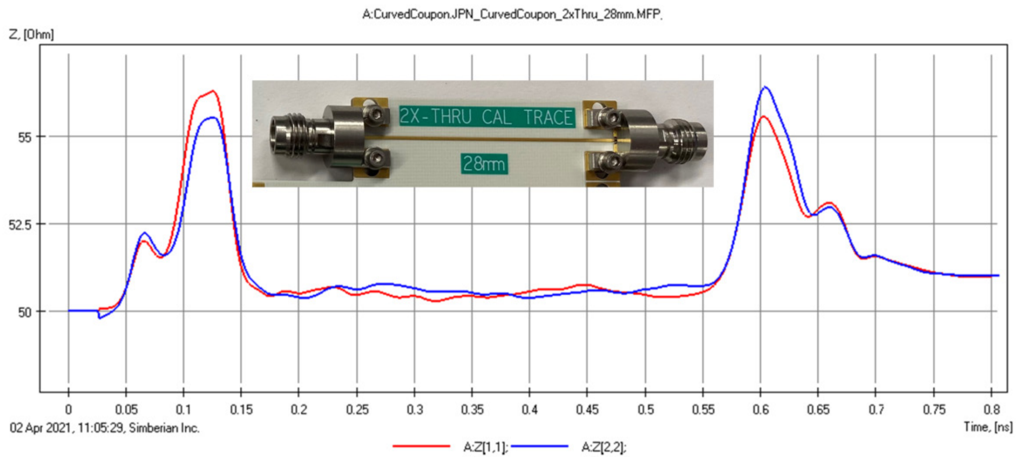

Fig. 12. TDR of 2x-through structure from the opposite end computed from measured S-parameters – shows violation of symmetry and differences with the de-embedded structures.

This simple experiment basically demonstrates what is possible in PCB realm when it comes to the analysis to measurements correlation. Measurements with high quality are done by Advantest with the state of the art de-embedding. Good analysis to measurement correlation was demonstrated for relatively reflective bends – uncompensated and mitered (with not so optimal positon of the cut). However, we were not able to get definite conclusion for the curved bend due to the geometry variations in the test fixtures. Nevertheless, such models are reliable (my biased opinion☺).

1. Y. Shlepnev, How Interconnects Work: How Interconnects Work: Minimal-reflection 90-degree bends in strip lines, Simberian App Note #2021_01, March 2, 2021 https://www.simberian.com/AppNotes/HowToMakePerfectBends-2021-03-02.pdf
2. H. Barnes, G. Bianchi, J. Moreira, A Review of 90 Degree Corner Design for High-Speed Digital and mmWave Applications, IEEE EPEPS 2020 https://ieeexplore.ieee.org/document/9231371
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4. Y. Shlepnev, S. McMorrow, Nickel characterization for interconnect analysis. - Proc. of the 2011 IEEE International Symposium on Electromagnetic Compatibility, Long Beach, CA, USA, August, 2011, p. 524-529.