On the validity of bisection-based thru-only de-embedding

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***Abstract*— The validity of the thru-only de-embedding method that uses mathematically bisected halves of a left-right symmetric THRU pattern is assessed in this paper. The popularly used Π-equivalent representation of a THRU and the bisection thereof is neither unique nor its validity firmly established. It is shown that an equally simple T-equivalent-based bisection gives better results than the Π-equivalent-based bisection by comparing the two bisecting methods with a result obtained from an independent method. The thru-only de-embedding method is also compared with the conventional open-short and short-open methods, and the interrelationship among them expected from the assumed equivalent circuit representations of the relevant dummy patterns is confirmed. This is made possible by using the odd-mode responses of symmetric 4-port devices as the 2-ports under study. This way, nonidealities associated with ordinary 2-port dummy patterns is avoided.**

I. Introduction

The bisection-based thru-only de-embedding method used in [1]–[5] is very simple and gaining popularity. It requires only one dummy pattern: THRU. The THRU is modeled with a Π-equivalent and split into symmetric halves as shown in Fig. 1 through simple algebra. The simplicity is a great advantage of this method. The multiport de-embedding method that makes use of decomposition of a $2n$-port into n uncoupled 2-ports suggested the use of this bisection-based thru-only method after decomposition [6], [7].

Note, however, that hardly any justification has been given for the validity of the Π-equivalent-based bisection (Fig. 1). Actually, it is also possible to bisect the THRU using, for instance, a T-equivalent (Fig. 2) as was done in [9]. While the THRU as a whole can be represented both by the Π-equivalent and the T-equivalent (recall the well-known T-Π or Y-Δ transformation for a linear 2-port), the halves of the THRU resulting from the Π-equivalent-based bisection (Fig. 1) and the T-equivalent-based bisection (Fig. 2) are not the same. The T-equivalent-based bisection, therefore, gives different de-embedded results than those from the Π-equivalent-based bisection. As a matter of fact, there are other ways of bisecting the THRU, and each of them might give a different result. This is because three complex numbers are required to represent an arbitrary linear reciprocal 2-port (i.e. a half of the THRU in this case), whereas the halves in Fig. 1 or Fig. 2 have less degrees of freedom, namely, only two complex numbers. Since it is impossible to uniquely determine the six unknowns (real numbers) that represent one half of a THRU from a measurement of an entire THRU alone, there is no guarantee that the midpoint of the THRU found by, say, the Π-equivalent-based bisection (Fig. 1) is any closer to the *actual* midpoint than those found by other bisecting procedures. A more elaborate bisecting procedure reported in [10] should also have the same problem. Clearly, the validity of some bisecting procedure must be established for the bisection-based thru-only de-embedding to be used reliably.

Another aim of this work is to clarify the relationship between the thru-only method and the conventional open-short [8] or short-open method [3]. In [3], Tretiakov et al. compared the Π-equivalent-based thru-only method, the open-short method, and the short-open method. Since the open-short method uses a variant of the Π-equivalent (Fig. 3) circuit to represent the parasitics to be removed, the result from the Π-equivalent-based bisection should be close to that from the thru-only method. However, [3] reports no such correspondence. We suspect that this is due to nonidealities of dummy patterns and that the correspondence does show up in better controlled situations. Fig. 4

In this paper, we assess the validity of the Π- and T-equivalent-based bisecting of THRU and show that the use of T-equivalent is better, at least for the on-chip differential transmission lines that we measured. We also show the relationship between the thru-only method and open-short or short-open method using the odd mode responses of symmetric 4-port devices.

II. Bisection-based thru-only de-embedding

Suppose that the as-measured T-matrix (transfer matrix) of the 2-port containing the device under test (DUT) can be

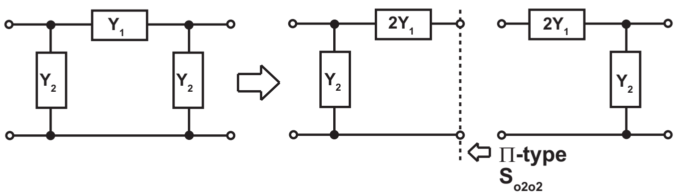

Fig. 1. Π-equivalent-based bisection of symmetric THRU.

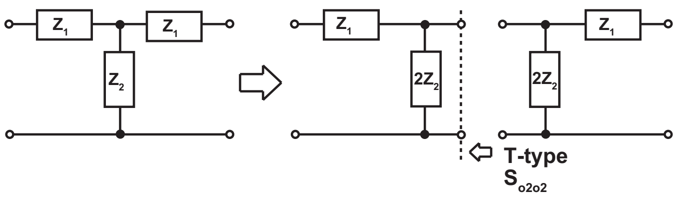

Fig. 2. T-equivalent-based bisection of symmetric THRU.

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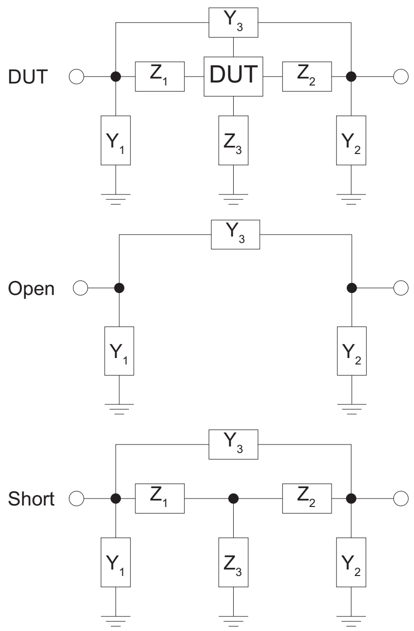

Fig. 3. Open-short de-embedding. $\boldsymbol{Z}_{\rm dut} = (\boldsymbol{Y}_{\rm meas} - \boldsymbol{Y}_{\rm open})^{-1} - (\boldsymbol{Y}_{\rm short} - \boldsymbol{Y}_{\rm open})^{-1}$.

represented as

$$\boldsymbol{T}_{\rm meas} = \boldsymbol{T}_{\rm L}\boldsymbol{T}_{\rm dut}\boldsymbol{T}_{\rm R} \tag{1}$$

and that the T-matrix of the THRU can be represented as

$$\boldsymbol{T}_{\rm thru} = \boldsymbol{T}_{\rm L}\boldsymbol{T}_{\rm R}. \tag{2}$$

Suppose also that the THRU is invariant under swapping of the two ports. If $\boldsymbol{T}_{\rm L}$ and $\boldsymbol{T}_{\rm R}$ can somehow be determined, the characteristics of the DUT can be de-embedded by

$$\boldsymbol{T}_{\rm dut} = \boldsymbol{T}_{\rm L}^{-1}\boldsymbol{T}_{\rm meas}\boldsymbol{T}_{\rm R}^{-1}. \tag{3}$$

The Π-equivalent-based bisection splits $\boldsymbol{T}_{\rm thru}$ into two symmetric halves as shown in Fig. 1. Then, $\boldsymbol{T}_{\rm L}$ and $\boldsymbol{T}_{\rm R}$ can be determined through simple algebra [1]–[5]. In terms of Y-matrices,

$$\boldsymbol{Y}_{\rm thru} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} = \begin{bmatrix} Y_1 + Y_2 & -Y_1 \\ -Y_1 & Y_1 + Y_2 \end{bmatrix}, \tag{4}$$

$$\boldsymbol{Y}_{\rm L\Pi} = \begin{bmatrix} Y_{11} - Y_{21} & 2Y_{21} \\ 2Y_{21} & -2Y_{21} \end{bmatrix}, \tag{5}$$

$$\boldsymbol{Y}_{\rm R\Pi} = \begin{bmatrix} -2Y_{21} & 2Y_{21} \\ 2Y_{21} & Y_{11} - Y_{21} \end{bmatrix}. \tag{6}$$

Similarly, the T-equivalent can be used to bisect the THRU and determine $\boldsymbol{T}_{\rm L}$ and $\boldsymbol{T}_{\rm R}$. The Z-matrix $\boldsymbol{Z}_{\rm thru} = \boldsymbol{Y}_{\rm thru}^{-1}$ of the THRU is

$$\boldsymbol{Z}_{\rm thru} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} = \begin{bmatrix} Z_1 + Z_2 & Z_2 \\ Z_2 & Z_1 + Z_2 \end{bmatrix}. \tag{7}$$

Then, the Z-matrices of the left and the right halves of the T-equivalent shown in Fig. 2 are

$$\boldsymbol{Z}_{\rm LT} = \begin{bmatrix} Z_{11} + Z_{21} & 2Z_{21} \\ 2Z_{21} & 2Z_{21} \end{bmatrix} \tag{8}$$

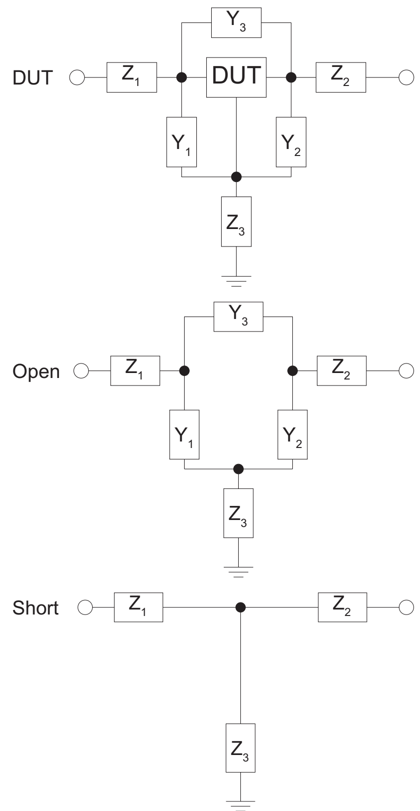

Fig. 4. Short-open de-embedding. $\boldsymbol{Y}_{\rm dut} = (\boldsymbol{Z}_{\rm meas} - \boldsymbol{Z}_{\rm short})^{-1} - (\boldsymbol{Z}_{\rm open} - \boldsymbol{Z}_{\rm short})^{-1}$.

and

$$\boldsymbol{Z}_{\rm RT} = \begin{bmatrix} 2Z_{21} & 2Z_{21} \\ 2Z_{21} & Z_{21} + Z_{22} \end{bmatrix}. \tag{9}$$

However, as mentioned earlier, the results from the two representations of THRU are different, that is $\boldsymbol{Z}_{\rm LT} \neq \boldsymbol{Y}_{\rm L\Pi}^{-1}$ and $\boldsymbol{Z}_{\rm RT} \neq \boldsymbol{Y}_{\rm R\Pi}^{-1}$. To visualize the difference, Fig. 5 plots the odd-mode reflection coefficient of the right-hand side port ($S_{\rm o2o2}$) of the left half of the THRU pattern shown in Fig. 6. The definition of $S_{\rm o2o2}$ is given in the Appendix. As can be clearly seen, the two left halves of the THRU, seen from the midpoint, are not the same. In other words, the midpoints reached by different bisecting methods do not necessarily coincide.

Which result is closer to the actual characteristics of the half of the THRU must be determined from more measurement data. After all, this is why rigorous calibration procedures like TRL [11] requires three or more on-wafer standards. In this work, we use the thru-line method [13], which requires only two standards, to generate reference data for comparison.

III. Comparison with other methods

In this work, we use a coplanar-strip line [14], shown in Fig. 6, as the DUT. It is a 4-port device that has even/odd symmetry. The line's nominal odd-mode characteristic impedance is $50\,\Omega$. The THRU pattern is also shown in Fig. 6. The pads have the ground-signal-ground-signal-ground (GSGSG) configuration.

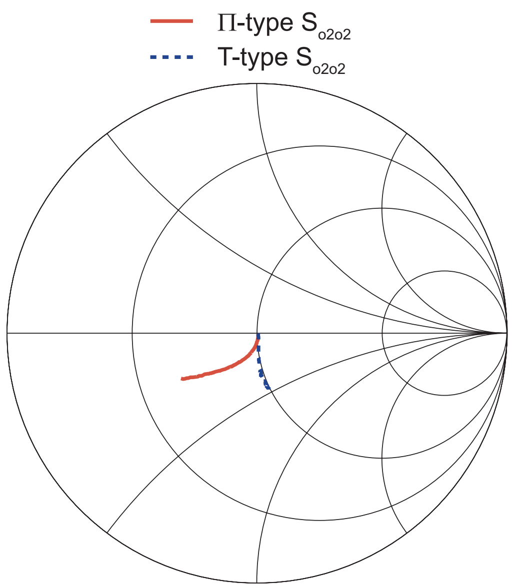

Fig. 5. $S_{\mathrm{o}2\mathrm{o}2}$ of the left half of the THRU shown in Fig. 6. The solid line is the result of Π-equivalent-based bisection (Fig. 1). The broken line is the result of T-equivalent-based bisection (Fig. 2).

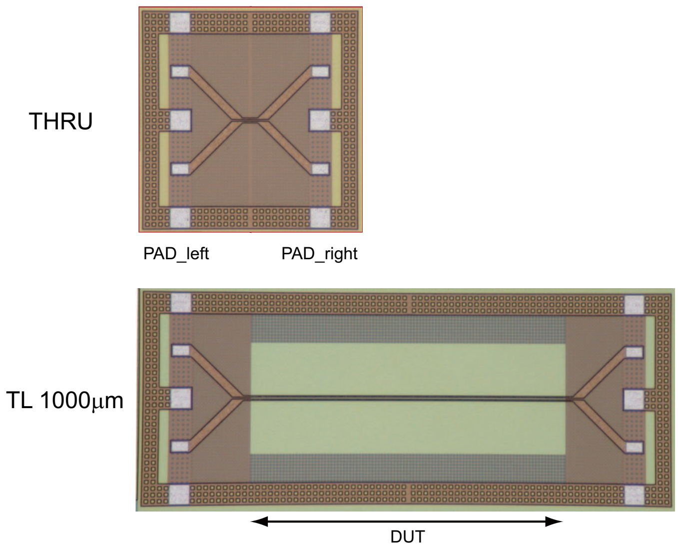

Fig. 6. Photographs of a THRU and a 1000-μm-long coplanar-strip line in 0.18 μm CMOS.

The thru-line method requires a THRU pattern and a transmission line pattern [13]. In contrast with the thru-only method, the former technique does not involve bisecting of the THRU pattern, and the midpoint problem can be avoided. The transmission line standard used in method has to have a known characteristic impedance. We will show later that the the odd-mode characteristic impedance is approximately 50 Ω.

The open-short and short-open de-embedding methods use the OPEN and SHORT patterns. These methods tend to result in overcompensation of parasitics, particularly due to the nonidealities of the SHORT pattern [5], [12]. The SHORT often contains unaccounted parasitic elements that contribute extra

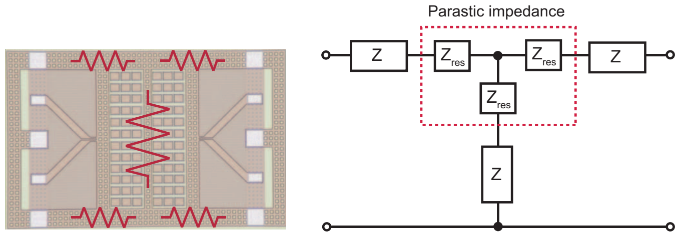

Fig. 7. Photograph of SHORT pattern and equivalent circuit with parasitic impedance.

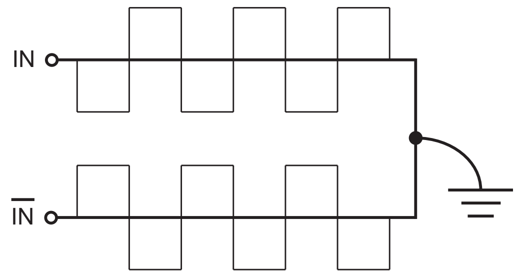

Fig. 8. Odd-mode SHORT pattern.

resistance and phase rotation at high frequencies (Fig. 7).

In general, we utilize a coplanar-strip line as a differential transmission line. The odd-mode characteristics, therefore, are more important. In this work, we use the odd-mode characteristics of differential devices [6]. In the odd mode, the shorting point at middle of the SHORT pattern becomes virtual ground (Fig. 8), and the size of the metal strip that shorts the lines is very small. Thus, parasitic impedance and phase rotation can be minimized.

Fig. 9 shows the odd-mode transmission coefficient $S_{\mathrm{o}2\mathrm{o}1}$ (see Appendix) of coplanar-strip transmission lines, de-embedded by the thru-line method [13]. Three lines of different lengths were used in the calculation, and all the results were consistent as shown.

Fig. 10 shows that the results from the Π-based thru-only method and the open-short method agree well. This is reasonable because both methods use similar Π-type equivalent circuits to represent the parasitics. Likewise, Fig. 11 shows that the results from the T-based thru-only method and the short-open method agree well. Our results are different from the results of [3]. We think that the difference originates in the different properties of the odd mode of our devices and the 2-port devices used in [3], which should behave similarly to the even mode of our 4-port devices.

Fig. 12 shows the odd-mode characteristic impedances of transmission lines obtained by using the Π-equivalent-based thru-only method, and Fig. 13 shows those from the T-equivalent-based method. Fig. 12 and Fig. 13 indicate that the odd-mode characteristic impedance is approximately 50 Ω. So the thru-line method can be applied.

Fig. 14 compares the $S_{\mathrm{o}2\mathrm{o}1}$ of a coplanar-strip line shown in Fig. 6, obtained by the Π-based thru-only, T-based thru-only, and thru-line methods. The results from the T-based

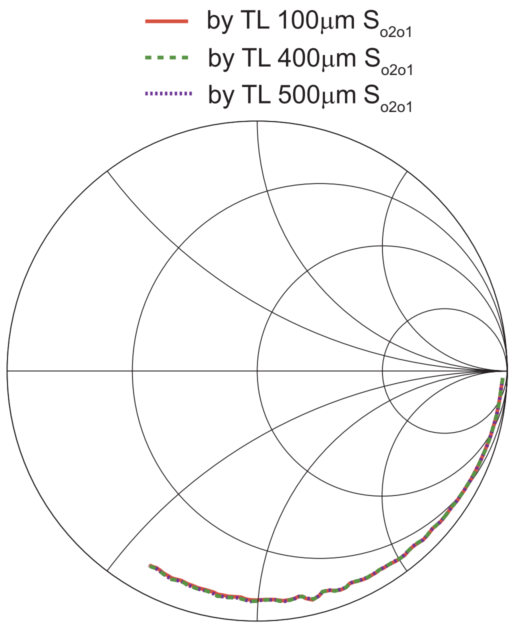

Fig. 9. Transmission line characteristics obtained by using the thru-line method with different lengths of dummy lines.

thru-only and the thru-line methods agree very well. This suggests that the use of the T-equivalent is better than the more popular Π-equivalent. Incidentally, this is consistent with the observation [15] that the short-open method is better than the open-short method.

IV. Conclusions

We studied the validity of bisection-based thru-only de-embedding. After pointing out the fact that the validity of the popularly used Π-equivalent-based bisection of a THRU (Fig. 1) is not established, we compared the Π-equivalent-based bisection with the T-equivalent-based bisection (Fig. 2). It turned out that the T-equivalent-based bisection gives better results. We also demonstrated the close correspondences (i) between the T-equivalent-based thru-only method and the short-open method and (ii) between the Π-equivalent-based thru-only method and the short-open method. These were done by looking at the odd-mode responses of on-chip dummy patterns and differential transmission lines because, then, some nonidealities associated with the ground conductor can be avoided.

How to deal with the even mode of differential devices or real 2-port devices needs more study.

Appendix

The even-mode and the odd-mode voltages and currents of a 4-port are related to the conductor-domain or as-measured voltages and currents by [6]

$$\boldsymbol{v} = \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \boldsymbol{K}_{\mathrm{Ve/o}} \boldsymbol{v}_{\mathrm{e/o}}, \tag{10}$$

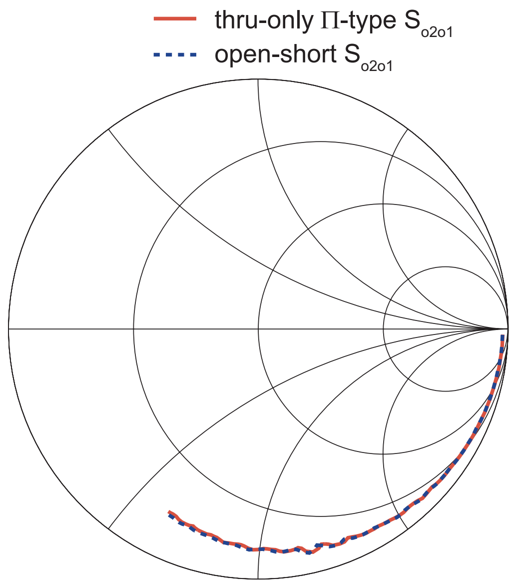

Fig. 10. De-embedded odd-mode transmission coefficient S_{o2o1}. Π-based thru-only and open-short.

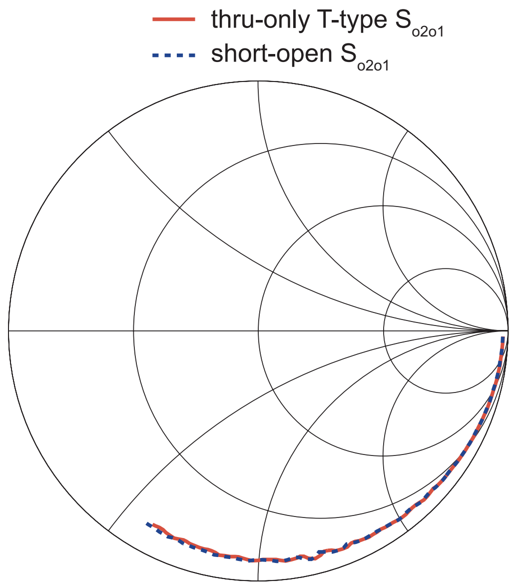

Fig. 11. De-embedded odd-mode transmission coefficient S_{o2o1}. T-based thru-only and short-open.

$$\boldsymbol{i} = \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \boldsymbol{K}_{\mathrm{Ie/o}} \boldsymbol{i}_{\mathrm{e/o}}, \tag{11}$$

$$\boldsymbol{K}_{\mathrm{Ve/o}} = \boldsymbol{K}_{\mathrm{Ie/o}} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \end{bmatrix}, \tag{12}$$

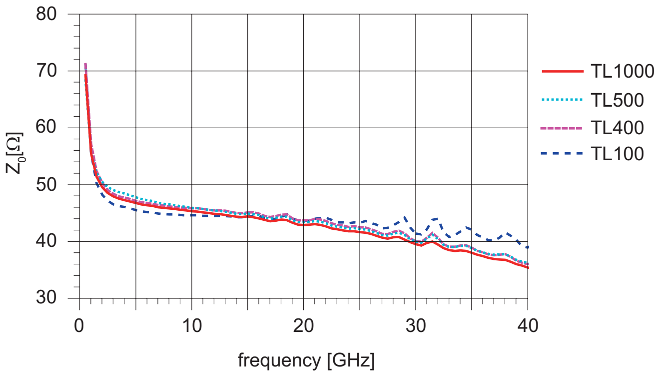

Fig. 12. De-embedded odd-mode characteristic impedance from the Π-equivalent-based thru-only de-embedding.

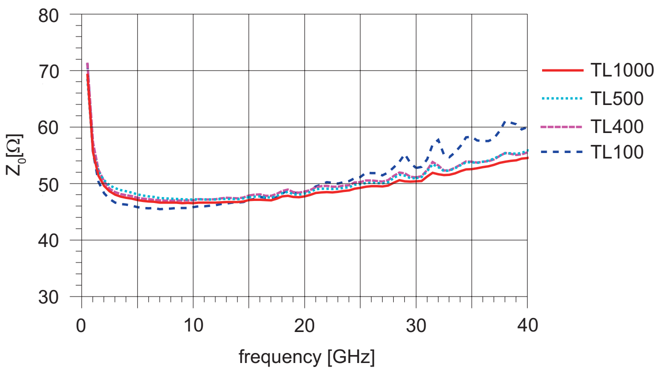

Fig. 13. De-embedded odd-mode characteristic impedance from the T-equivalent-based thru-only de-embedding.

$$\boldsymbol{v}_{\mathrm{e/o}} = \begin{bmatrix} V_{\mathrm{e1}} \\ V_{\mathrm{e2}} \\ V_{\mathrm{o1}} \\ V_{\mathrm{o2}} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} V_1 + V_3 \\ V_2 + V_4 \\ V_1 - V_3 \\ V_2 - V_4 \end{bmatrix}, \tag{13}$$

$$\boldsymbol{i}_{\mathrm{e/o}} = \begin{bmatrix} I_{\mathrm{e1}} \\ I_{\mathrm{e2}} \\ I_{\mathrm{o1}} \\ I_{\mathrm{o2}} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} I_1 + I_3 \\ I_2 + I_4 \\ I_1 - I_3 \\ I_2 - I_4 \end{bmatrix}. \tag{14}$$

Suppose $\boldsymbol{S}$ is an as-measured S-matrix of a 4-port.

$$\boldsymbol{S} = \begin{bmatrix} \boldsymbol{S}_{11} & \boldsymbol{S}_{12} \\ \boldsymbol{S}_{21} & \boldsymbol{S}_{22} \end{bmatrix} = \left[\begin{array}{cc|cc} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ \hline S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{array}\right]. \tag{15}$$

The corresponding S-matrix in the even/odd domain, $\boldsymbol{S}_{\mathrm{e/o}}$, is given by the following orthogonal transformation [6].

$$\boldsymbol{S}_{\mathrm{e/o}} = \boldsymbol{K}_{\mathrm{Ve/o}} \boldsymbol{S} \boldsymbol{K}_{\mathrm{Ve/o}} = \begin{bmatrix} \boldsymbol{S}_{\mathrm{ee}} & \boldsymbol{S}_{\mathrm{eo}} \\ \boldsymbol{S}_{\mathrm{oe}} & \boldsymbol{S}_{\mathrm{oo}} \end{bmatrix} \tag{16}$$

$$= \left[\begin{array}{cc|cc} S_{\mathrm{e1e1}} & S_{\mathrm{e1e2}} & S_{\mathrm{e1o1}} & S_{\mathrm{e1o2}} \\ S_{\mathrm{e2e1}} & S_{\mathrm{e2e2}} & S_{\mathrm{e2o1}} & S_{\mathrm{e2o2}} \\ \hline S_{\mathrm{o1e1}} & S_{\mathrm{o1e2}} & S_{\mathrm{o1o1}} & S_{\mathrm{o1o2}} \\ S_{\mathrm{o2e1}} & S_{\mathrm{o2e2}} & S_{\mathrm{o2o1}} & S_{\mathrm{o2o2}} \end{array}\right]. \tag{17}$$

$\boldsymbol{S}_{\mathrm{oo}}$ is the odd-mode S-matrix.

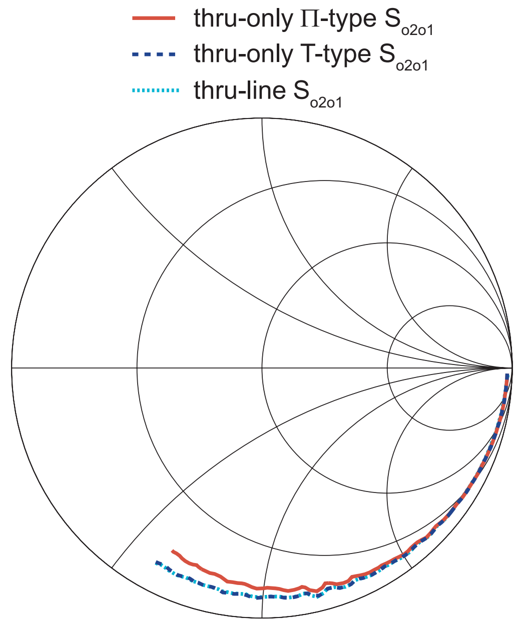

Fig. 14. De-embedded odd-mode transmission coefficient S_{o2o1} of a coplanar-strip line. Π-equivalent-based thru-only, T-equivalent-based thru-only, and thru-line methods were used.

Unlike the common/differential transformation (e.g. [16], [17]), the even/odd transformation does not affect the reference impedance matrix [6]. More detailed discussions can be found in [18].

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