Electromagnetic Design of
flexIble SensOrs

Report 2.
Analysis of Software Calibration Ports Using Short Open Method

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1 Introduction

The aim of the report is showing the calibrations techniques and the results of numerical experiments.

This document has focused on the method short-open-calibration[1]. This technique de-embedding is directly inspired by the physical calibration algorithm, using a two standards loads (i.e., short-end and open-end circuits) with precisely known characteristics.

1.1 Procedure of the Short-Open calibration

The standard calibration procedure is based on finding the error box (expressing discontinuities)[2], for our the DUT (device-under-test may by circuit network), which will be an example the microstrip transmission line.

In order to determine single port discontinuity, in the simulation procedure to DUT we add a small section of the transmission line which next we will be remove from DUT in the procedure de-embedding together with port discontinuity.

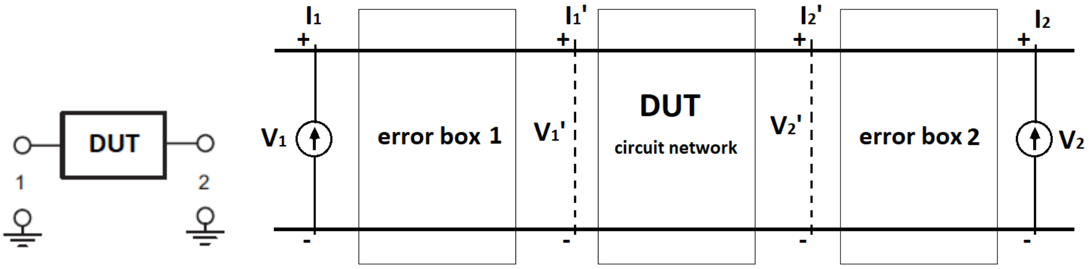


Figure 1: The general scheme of the system and the idea of short-open-calibration. Line of a small length is attached to the circuit as an error box.

In the next step, we perform two separated simulations. In two configurations: properly short and open the end of this a small line.

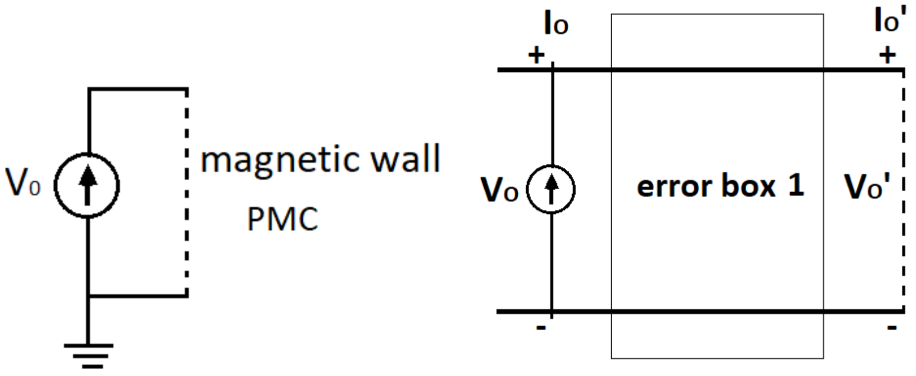


Figure 2: In the ideal case open-end the current has a value $I'_O = 0$

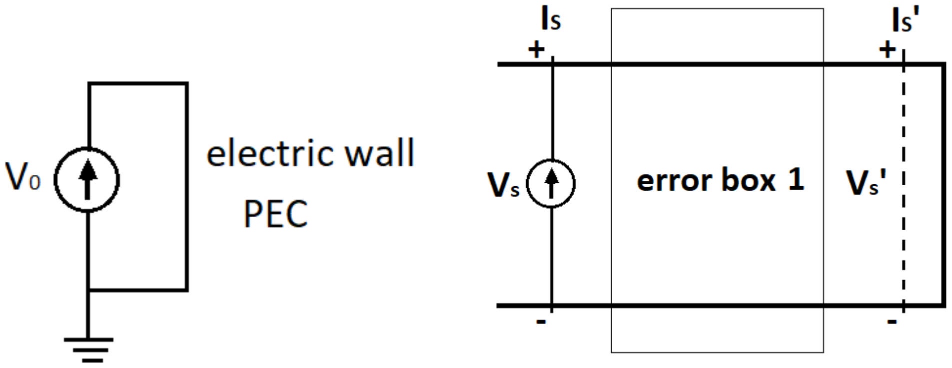


Figure 3: In the ideal case short-end the voltage has a value $V_S' = 0$

In full-wave-simulators (InventSim, HFSS), short-end and open-end circuits can be exactly realised by means of perfect electric and perfect magnetic wall (set as a boundary condition at the end of the line).

2 De-embedding - implementations SOC method

The results of simulation obtained will be used during the calibration procedure. Analysing circuit parameters (i.e, voltage, current, impedance) we will use the concept as a two-port network.

2.1 Circuit theory

In generally, the current wave and the voltage wave consist of an incident wave and a reflected wave.

$$I = I^+ - I^- \tag{1}$$

$$U = U^+ + U^- \tag{2}$$

In the circuit model, the lumped port can be described by a voltage source V_0 with a specific internal resistance Z_0. This impedance is normalized to 50Ω. To the port in cross-section $d = 0$ we attach a structure described by the matrix S (obtained in a full wave simulation) and some load with the impedance Z_L in the cross-section $d = L$.

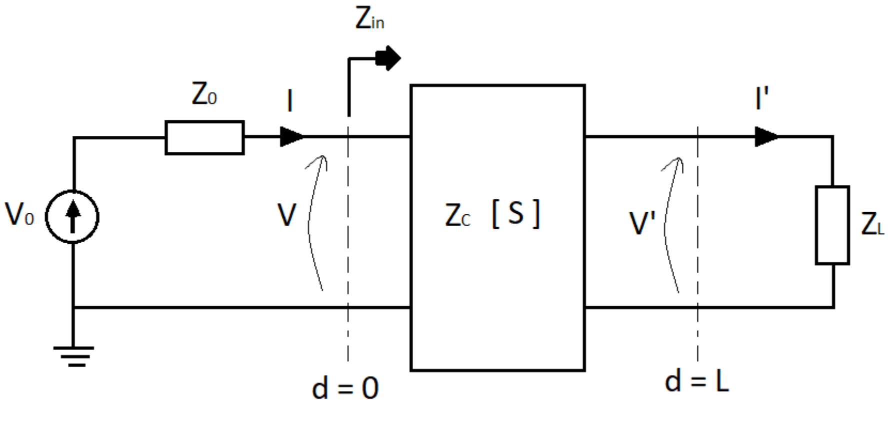
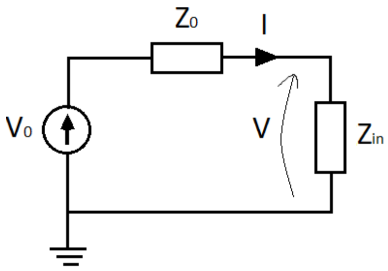


Figure 4: The DUT described by the S matrix has the determined characteristic impedance Z_C

By impedance transformation on the input terminals, some Z_{in} impedance is visible.

$$Z_{in} = Z_0 \frac{1 + |S_{11}|}{1 - |S_{11}|} \tag{3}$$



Having calculated the voltage V in the port cross-section and the Z_{in} impedance, we are able to count the current flowing in a given cross-section of the system. From Ohm's law, this is the voltage to impedance relationship.

$$I = \frac{V}{Zin} \tag{4}$$

2.2 Two-port network theory

There are some properties of two-ports, which often occur in circuits description, can be simplified considerably and used in the analysis. We will use the transmission ABCD matrix[3].

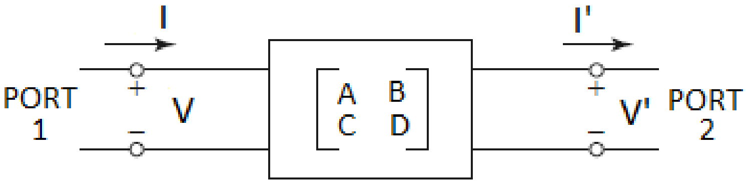


Figure 5: The ABCD matrix is defined for a two-port network in terms of the total voltages and currents as shown and the following in matrix form as:

$$\begin{bmatrix} V \\ I \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V' \\ I' \end{bmatrix} \tag{5}$$

$$\begin{gathered} V = AV' + BI' \\ I = CV' + DI' \end{gathered} \tag{6}$$

When the are reciprocal networks, the four elements of their respective ABCD matrix are related as:

$$AD - BC = 1 \tag{7}$$

2.3 Transformation of equations in the SOC procedure

After simulation short-end and open-end we are able to determine the voltage (look. 3.1) and current with Ohm's law relationship (look. 2.1) in a given cross-section of system. We get the following system of equations :

$$\begin{cases} V_s = AV_s' + BI_s' \\ I_s = AV_s' + DI_s' \\ \\ V_o = AV_o' + BI_o' \\ I_o = CV_o' + DI_o' \\ \\ AD - BC = 1 \end{cases} \tag{8}$$

Assuming the conditions for an ideal open circuit with Fig.2, the only unknown in this case is I'_O.

$$I_o^{'} = 0 \Longrightarrow \begin{cases} V_o = AV_o^{'} \\ I_o = CV_o^{'} \end{cases} \Longrightarrow \begin{cases} A = \frac{V_o}{V_o^{'}} \\ \\ C = \frac{I_o}{V_o^{'}} \end{cases} \tag{9}$$

we make simple transformations

$$\begin{cases} V_s = AV_s^{'} + BI_s^{'} \\ I_s = AV_s^{'} + DI_s^{'} \\ AD - BC = 1 \end{cases} \Longrightarrow \begin{cases} B = \frac{V_s - AV_s^{'}}{I_s^{'}} \\ D = \frac{I_s - CV_s^{'}}{I_s^{'}} \end{cases} \tag{10}$$

and calculate the necessary current at the output in case of I'_S short circuit.

$$A(I_s - CV_s^{'}) - C(V_s - AV_s^{'}) = I_s^{'} \tag{11}$$

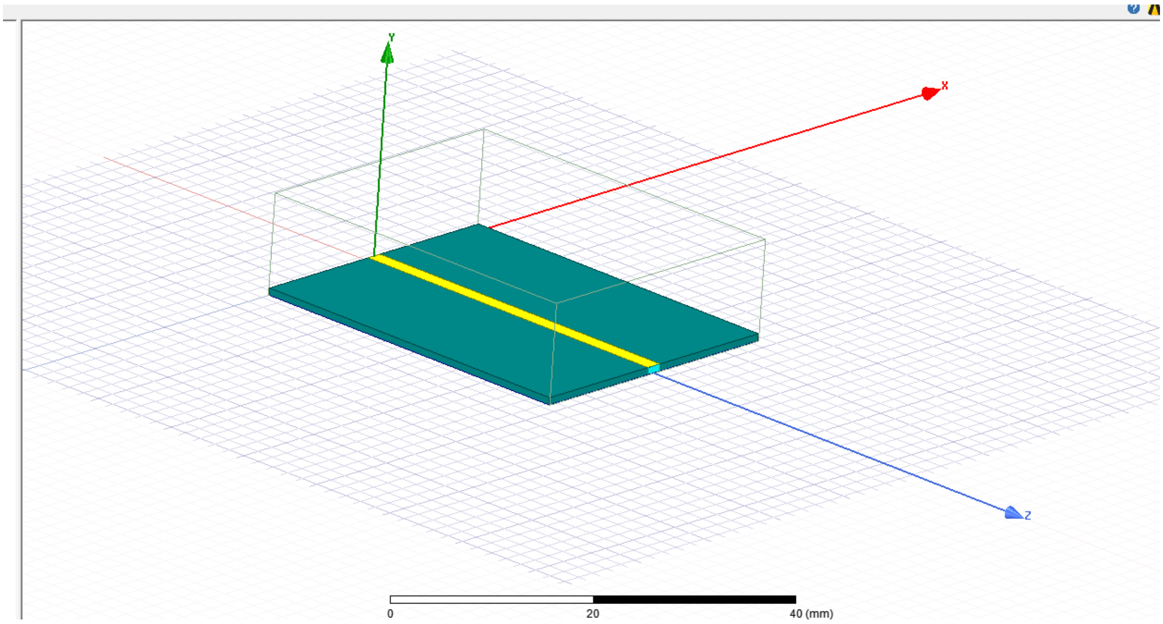
In this way, we finally get an ABCD matrix whose coefficients can be calculated by the following expressions:

$$\begin{array}{l} A = \frac{V_o}{V_o^{'}} \\ C = \frac{I_o}{V_o^{'}} \\ I_s^{'} = A(I_s - CV_s^{'}) - C(V_s - AV_s^{'}) \\ B = \frac{V_s - AV_s^{'}}{I_s^{'}} \\ D = \frac{I_s - CV_s^{'}}{I_s^{'}} \end{array} \tag{12}$$

The obtained ABCD matrix corresponding to the error box, we subtract in the de-embedding procedure from the DUT. After it should be changed matrix ABCD on matrix S.

3 Simulation parameters

Currently for testing purposes simulations were performed for a single microstrip line in commercial software HFSS. At a later stage of the work, the identical simulation will be performed, also in InventSim.



For test simulations were assumed substrate which is available in department for the purpose of physical realization, and measurement. Structure parameters:

- substrate : laminat ISOLA I-TERAMT 3.45 0300 XHB
- thickness of the substrate : $0.762mm$
- permeability : 3.45
- width strip : $1.72mm$ $(Z_c = 50\Omega)$
- DUT length line $\mathbf{L} = 36.405mm$
- OPEN and SHORT length line $\mathbf{L} = 1mm$
- DUT length line $\mathbf{L} = 36.405 + 1 + 1 = 38.405mm$

Simulation was made in the frequency range from $0.1GHz$ do $5GHz$ for the line parameters described above (with 101 points).

3.1 Voltage calculation in cross-section

Full wave simulators, (eg. InventSim and HFSS), in addition to the results in the form of a scattering matrix, also enable the export of data in the form of an electric and magnetic field vector at a given point in the space on a given frequency. Having vectors $\vec{E}, \vec{H}$ from of the simulation point by point, we can count the voltage in a given cross-section, using the basic laws of electrodynamics[4].

Assuming that the field is potential, the relationship between voltage and the function of the electric field, he describes :

$$\vec{E}(x, y, z) = -\vec{\nabla} U \tag{13}$$

Based on Stokes theorem, gradient potential can be converted to a line integral :

$$\Delta U = \int_L \vec{E} \circ \vec{dl} = \int_L E_x d_x + E_y d_y + E_z d_z \tag{14}$$

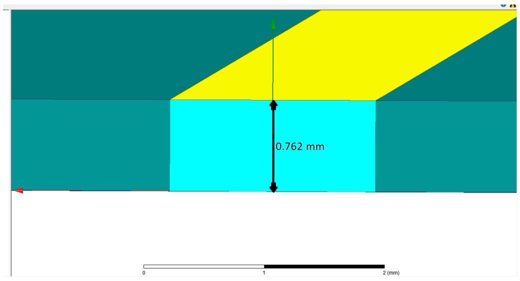


Figure 6: We integrate along the curve the plane of the port.

$$d_l = \begin{cases} 0 & for \quad x_{port}, x_{end} \\ dy & for \quad 0 < y < L_y \\ 0 & for \quad z_{port}, z_{end} \end{cases} \tag{15}$$

So it shortens to the equation:

$$\vec{E} \circ \vec{dl} = E_y d_y \tag{16}$$

As the field distribution is obtained in a discretised form:

$$d_y = \frac{L_y}{N} \tag{17}$$

where our calculations have been assumed,
N = number of points = 501
$L_y = 0.762mm$.
We exchange the integral into a sum:

$$\Delta U = \sum_{k=0}^{N} E_{yi}(x, k \cdot dl, z) d_y \tag{18}$$

3.2 Field intensity distribution

As previously shown in the Fig.6, the straight line along cross-section the of the port was assumed as the integration area.

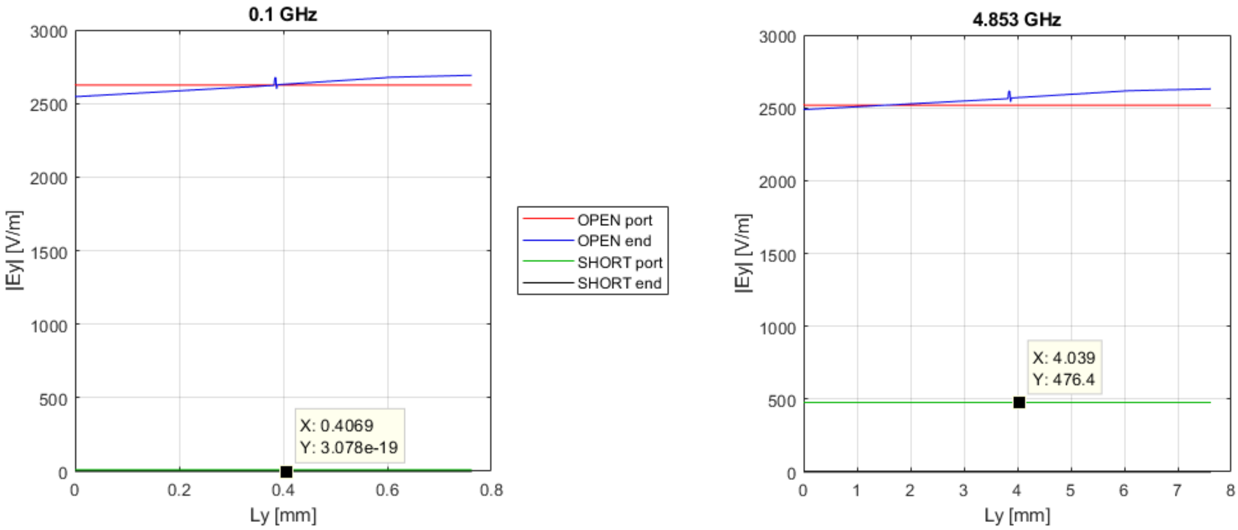


Figure 7: This is the results from HFSS, electric field in InventSim have ten times greater value (Identical tests have been carried out in InventSim).

According to theoretical assumptions for the short circuit, we have the minimum field density, while the maximum for open circuit. At higher frequencies it can be seen that a perfect short circuit has not been obtained (The electric field in the port is not zero). It may affect the correctness of the calibration result.

4 Calibration results

The above patterns and dependencies have been implemented in the form of a script in Matlab. The table below presents the results of circuits parameters for the lowest simulation frequency. Voltages and currents are used in the calibration process. The input impedance of the simulated system was determined based on the reflection coefficient. All values coincide with theory.

frequency of simulation : 100MHz

	DUT	**OPEN**	**SHORT**
S11	-0.0007 – 0.0038i	0.9999 - 0.0120i	-1.0000 + 0.0074i
$|S_{11}|$ [dB]	-48.2302	-1.7025e-04	-1.2443e-05
Zin	49.9289 - 0.3808i	1.3676e+01 – 8.3528e+03i	3.5815e-05 + 0.1857i
V (port)	-1.0013 - 0.0038i	-2.0039 - 0.0120i	-2.8778e-05 + 0.0074i
V' (end)	-0.9925 - 0.1364i	-2.0040 – 0.0120i	-5.1526e-11 + 1.4841e-08i
I (port)	-0.0201 - 0.0002i	1.0433e-06 - 2.3991e-04i	0.0399 + 0.0002i
I' (end)	-0.0199 - 0.0029i	0	0.0399 + 0.0002i
P (port)	0.0201 + 0.0003i	-4.9685e-06 + 4.8075e-04i	-2.3510e-06 + 2.9504e-04i

It can also be noticed that in the case of ports lumped in HFSS, a voltage equal to $V_0 = 1V$ is set on the source. In the case of open circuit, we have a wave amplification, i.e., the incident wave and the reflected wave are consistent in phase. As a result of their sum, we get $V_O \approx 2V$. However, for short circuit, these waves are in antiphase by which the sum of their voltage is equal to $V_S \approx 0V$.

The current value $I'_O(end) = 0$ for the open circuit case was assumed theoretically, whereas for short circuit was calculated from the formula (11).

4.1 De-embedding results

The results for two calibration methods are presented and compared below. Double delay described in the previous report and SOC, as well as the result before calibration DUT.

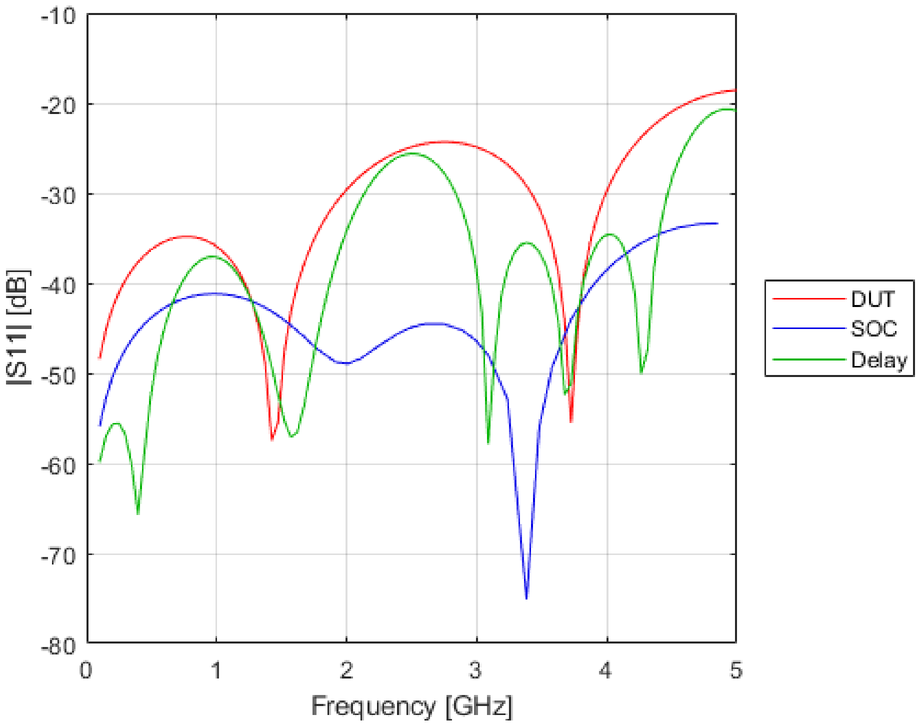


Figure 8: S_{11} reflectance module characteristics before and after line length **L** calibration using SOC and double dalay methods.

As you can see the results of the calibration give a positive effect, an improvement in the match is achieved, i.e. a lower of the reflection factor of the line. The shape of the phase characteristics is also improved.

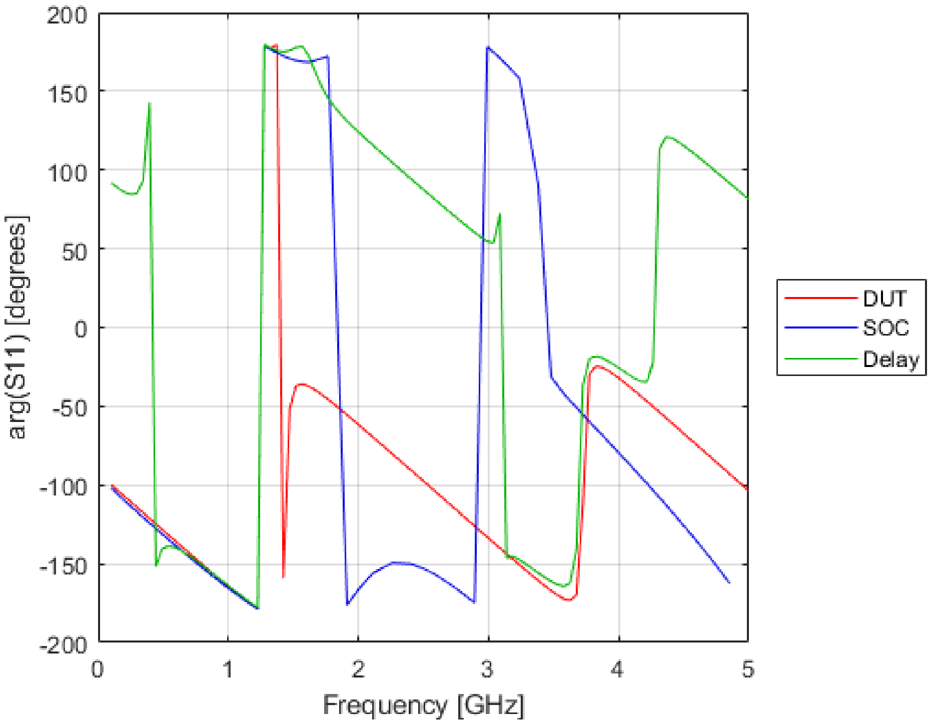


Figure 9: S_{11} reflectance phase characteristics before and after line length **L** calibration using SOC and double dalay methods.

The characteristic impedance [5] of the system is the relationship between the coefficients of the ABCD matrix.

$$Z_C = \sqrt{\frac{B}{C}} \tag{19}$$

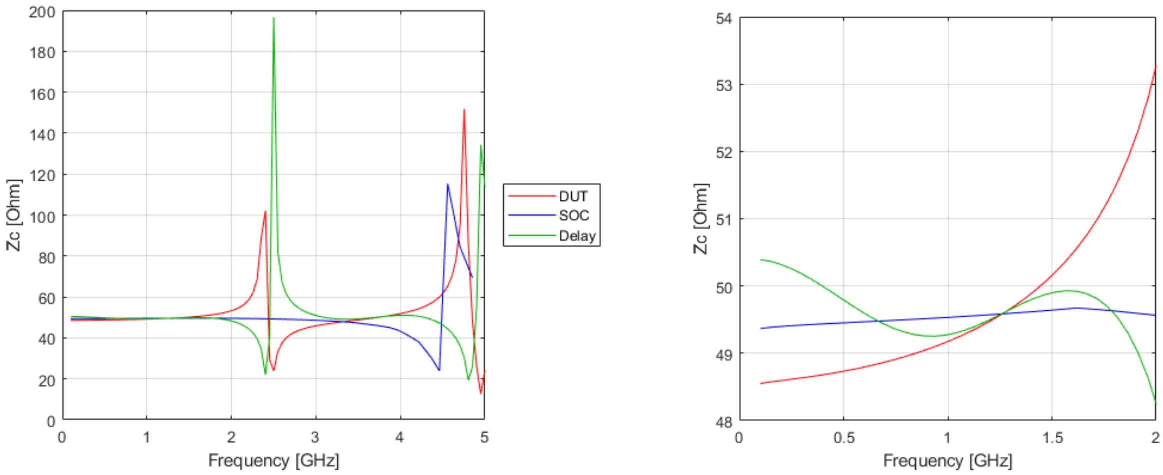


Figure 10: Characteristic impedance Z_o to before and after line length **L** calibration using SOC and double delay methods.

After SOC calibration, the characteristic impedance in general has a constant value similar to Z_0. This effect could not be obtained in the case of double delay.

5 Conclusion

For this particular case calibration procedure was successful. The generally it is necessary to make additional tests confirming the correctness of the implemented method.

In the next stage of work, several other sample structures will be simulated and calibration will be performed in InventSim. Currently the biggest problem with InventSim is the normalization of power source in the port relative to HFSS.

In the above SOC method, however, pre-processing of results (integral the field distribution) is necessary. In generally, due to the calibration of the lumped ports, it should be noted that with the higher frequencies the wave is getting shorter. The circuit model is becoming less accurate. As a result, for example, for lines with a length of $\frac{\lambda}{4}$, the short-circuit will change into an open.

References

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