EDISON

Electromagnetic Design of
flexIble SensOrs

FNP Team-Tech

Report 4.
Design of Planar Microwave Circuits using Software Calibrated Ports and even odd Excitation Analysis

Sebastian Dziedziewicz

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1 Introdaction

The aim of the report is showing the results from the final stage of creating a master's project. In the last period of work, the focus was on designing planar systems, using previously developed calibration techniques. At the same time, through the increasingly complex structures, it was possible to verify the correctness of de-embedding and compare the results with other simulators, and the later stage with the experiment (measurement). In short, the following tasks were performed:

- design, analysis and calibration of an exemplary microstrip line with stub
- review of the literature on the design of planar systems using their symmetry of the system and even, odd excitation analysis
- design and optimization (calibration) of an example 3dB branch coupler

2 Design of microstrip line with stub

In order to check the correctness of the performed calibration, a microstrip line with parallel stub design was created. The substrate to be used in simulation was Rogers 4003C. The serial line with an electrical length $\theta = 90^o$ (quarter-wavelength line) was selected for 3 GHz central frequency. The attached parallel line has an electrical length $\theta = 180^o$ (half-wavelength line).

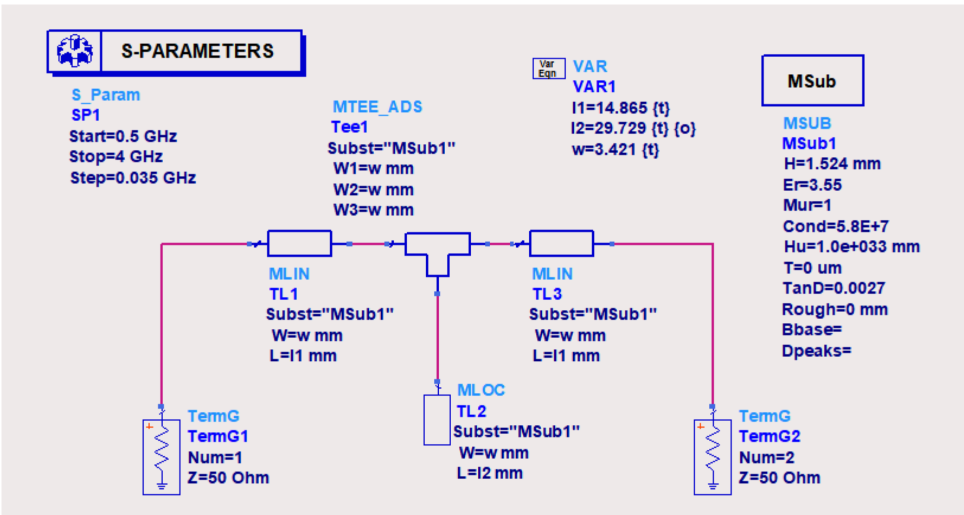


Figure 1: System schematic with all parameters of the simulated structure.

The design of the ideal circuit network in ADS was first carried out. Based on it, a layout was generated to simulate it in Momentum. The next step was to draw the same project in InventSim and HFSS (in order to compare the results). In all of this simulators, we used the available calibration. In InvenSim, the calibration was performed manually using the Double Delay technique. An error box was used for a single line "L", about the electrical length $\theta = 90^o$.

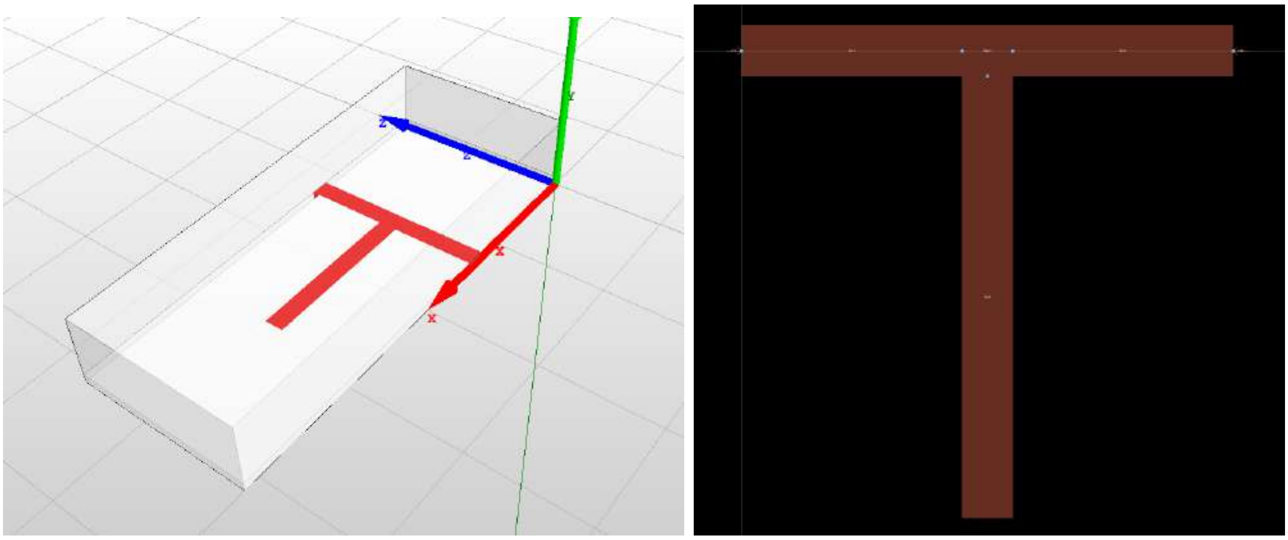


Figure 2: Designed structure model, on the left a screenshot from InventSim, on the right layout in Momentum.

2.1 Simulation Results

The simulation results are presented below, in the form characteristics of refection, transmission coefcients and phase. All of symulations carried out using direct solver (without fast frequency sweept) and adaptive meshing. Comparison of results from several simulators: ADS (circuit), Momentum (TML calibration), InventSim (lump port), HFSS (lump port with using calibration).

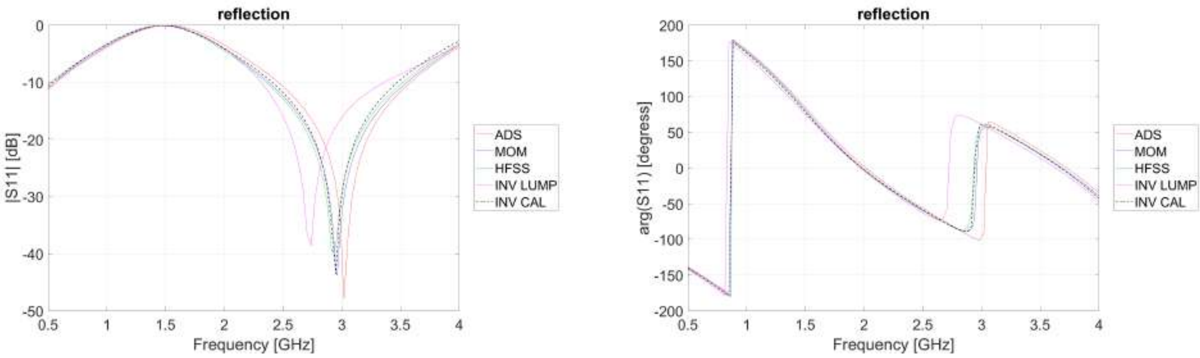


Figure 3: Obtained characteristics, module and phase of reflection coefficient S_{11}.

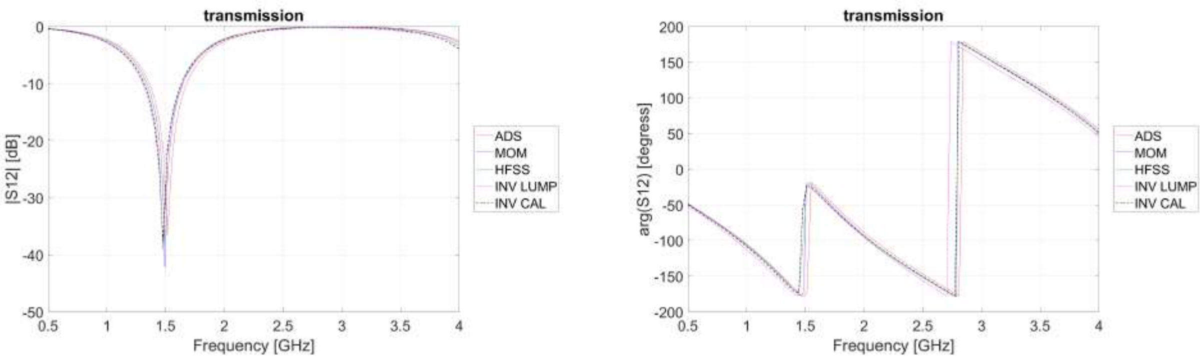


Figure 4: Obtained characteristics, module and phase of transmission coefficient S_{12}.

As you can see before the calibration, the obtained result from InventSum differs from the other simulators. After calibration, all results are convergent.

2.2 Microstrip line with stub and load

As part of the work on the lumped ports, one more test was carried out. In HFSS, it is possible to insert lumped elements in the 3D structure in the form of for example, capacitance or inductance. Such a simulation was made for a microstrip with stub , at the end of which a lumped capacitance was attached. For the purpose of the test 2pF was added, which corresponds to the simulation of eg. a diode or a varactor attached. In InventSim there is currently no such possibility, but a simulation was performed in which a lumped port was defined at the end of the stub. The response for the three-port network was determined, and then in a circuit way (using ADS), a lumped capacitance of the same value was added to the end of the stub (i.e. the port).

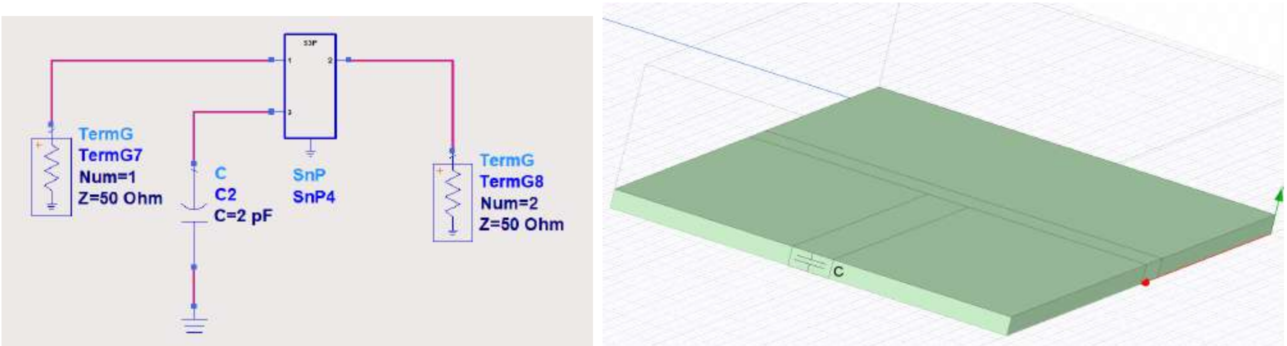


Figure 5: On the left, circuit schematic in ADS (the s3p file obtained from the simulation in InventSim was used), on the right screenshot from HFSS, with general the idea of attached lumped capacitance.

Furthermore, the lumped port was calibrated and checked whether both responses would be consistent.

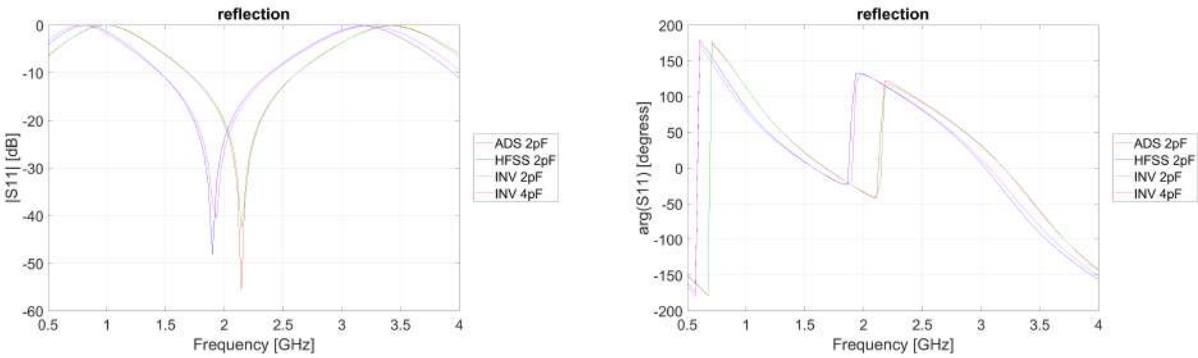


Figure 6: Obtained characteristics, module and phase of reflection coefficient S_{11}.

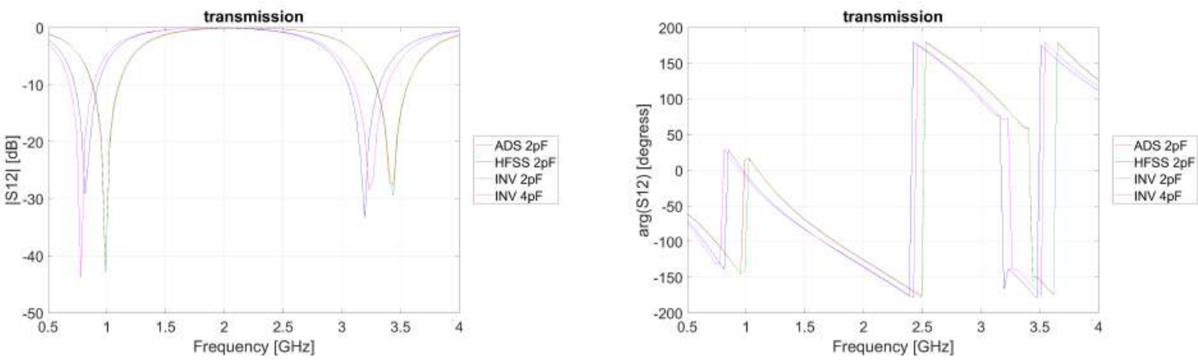


Figure 7: Obtained characteristics, module and phase of transmission coefficient S_{12}.

As you can see, the are results diverge, however the inclusion of the capacitance in the circuit in

ADS coincides with the three-port network from InventSim (after applying the calibration). The result from HFSS for capacitor 2pF is slightly divergent (although it is not specified how is modeling this in the simulator).

3 Branch Coupler

Couplers included in the group of power dividers, these are four-ports networks microwave devices that are widely used in mixers, amplifiers, detectors and in antenna technology. They allow to divide the signal power. A very important feature of these devices is also the fact that they can change the phase of the signal. The simplest in the implementation of this type of systems are branch couplers.

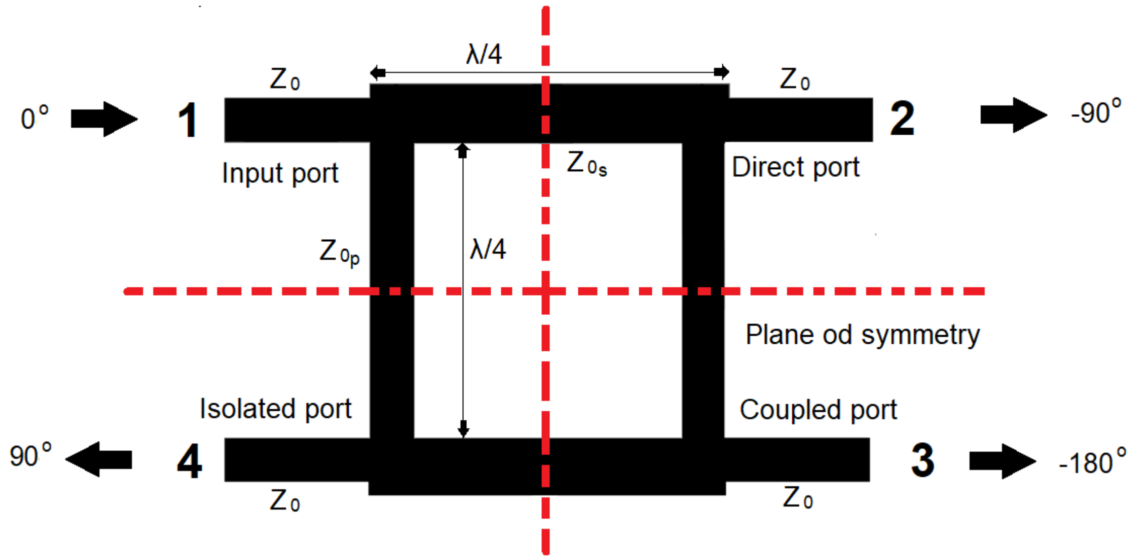


Figure 8: General branch coupler schematic, there are consists of four sections of transmission lines (quarter-wavelength line).

In general, when we are starting to the coupler design, it is basic parameters must be defined ie. reflection, transmissions, coupling and isolation (and also directionality and losses). The values of these coefficients depend directly on the impedance of individual sections of the transmission lines. The structure shown in the figure above can be described using the following scattering matrix[1]:

$$[\mathbf{S}] = -Z_{0s}\begin{bmatrix} 0 & \frac{j}{Z_0} & \frac{1}{Z_{0p}} & 0 \\ \frac{j}{Z_0} & 0 & 0 & \frac{j}{Z_{0p}} \\ \frac{1}{Z_{0p}} & 0 & 0 & \frac{j}{Z_0} \\ 0 & \frac{1}{Z_{0p}} & \frac{j}{Z_0} & 0 \end{bmatrix} \tag{1}$$

There are zero values on the main diagonal (resulting from the assumption of an ideal matching). The phase difference between output second and third port is 90 degrees, because $-j = e^{-90^o j}$ (phase shift from first to second port, $\theta = -90^o$) and $-1 = e^{-180^o j}$ (phase shift from first to third port, $\theta = -180^o$).

$$S_{21} = -j\frac{Z_{0s}}{Z_0}\ S_{31} = -j\frac{Z_{0s}}{Z_{0p}}$$

On this basis, the parameter K can be defined, determined in which ratio the signal should be divided.

$$K = \frac{|S_{21}|}{|S_{31}|} = \frac{Z_{0p}}{Z_0} \tag{2}$$

where, Z_0 it is usually the reference impedance (for an equal match 50Ω).

3.1 Three dB Quadrature Hybrid Coupler

One of the most popular couplers are three-decibel couplers. They are characterized by the fact that the power of the input signal is divided in half, between transmission and coupling. This has a lot of applications in microwave systems. The most popular is the use of such structures in Butler's matrixes or other types of antenna arrays, where the element is to shape the direction of the signal beam at the output (beamforming network). For the 3dB coupler, the impedances have the values of:

$$Z_0 = 50\Omega\ ,\ Z_{0p} = 50\Omega,\ Z_{0s} = \tfrac{50}{\sqrt{2}}\Omega$$

After normalization to Z_0 the scattering matrix has the following form:

$$[S] = \frac{-1}{\sqrt{2}} \begin{bmatrix} 0 & j & 1 & 0 \\ j & 0 & 0 & 1 \\ 1 & 0 & 0 & j \\ 0 & 1 & j & 0 \end{bmatrix} \tag{3}$$

3.2 Even odd excitation analysis

The principle of operation of couplers in which symmetry of the system takes place is based on the use of the property of a pair of coupling transmission lines, in which there the basic two types of field, even and odd are propagated simultaneously.

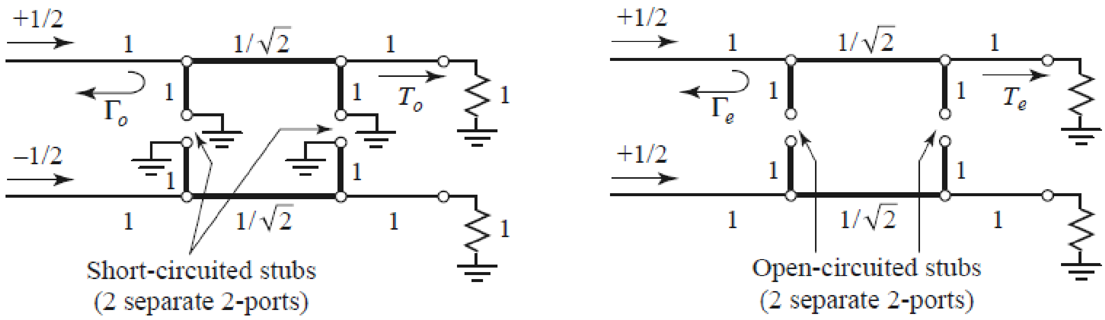


Figure 9: Cutting in the cross-section of the coupler structure, you can model in circuit theory both types of field by opening (even) and shorting (odd).

The even mode occurs when the waves propagate in lines in the same direction, while the odd mode is are in the opposite direction[2].

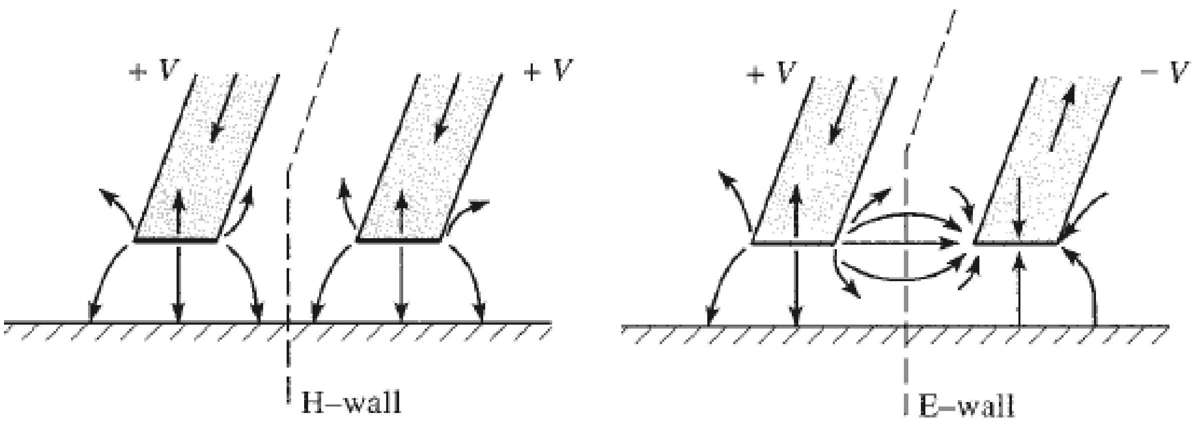


Figure 10: In the full-wave-simulators, short and open circuits can be exactly realised by means of perfect electric and perfect magnetic wall (set as a boundary condition at the side wall).

The mutual relation between the impedances characteristic of the even and odd modes affects the level of coupling obtained:

$$C[dB] = 20log\frac{Z_{0e} - Z_{0o}}{Z_{0e} + Z_{0o}} \tag{4}$$

and

$$Z_0 = \sqrt{Z_{0e}Z_{0o}} \tag{5}$$

where, Z_{0e}, Z_{0o}, Z_0 that is mean, characteristic impedance of the even, odd mode and reference impedance.

For the $C = 3dB$ coupling, these impedances have the following values:

$$Z_{0e} = Z_0\sqrt{\frac{1+C}{1-C}} = 120.9136\Omega \tag{6}$$

$$Z_{0o} = Z_0\sqrt{\frac{1-C}{1+C}} = 20.6759\Omega \tag{7}$$

Based on a scattering matrix, for even and odd modes (obtained from the simulation of half of the coupling line and using the method excitation) you can specify the S scattering matrix for a symmetric four-port network coupler through the following dependencies:

$$S_{11} = \frac{S^e_{11} + S^o_{11}}{2}, S_{12} = \frac{S^e_{12} + S^o_{12}}{2}, S_{13} = \frac{S^e_{12} - S^o_{12}}{2}, S_{14} = \frac{S^e_{11} - S^o_{11}}{2} \tag{8}$$

3.3 Implementation of the coupler project

As part of the work, a three-decibel branch coupler was designed on the 2.4GHz center frequency. First, a circuit model was created in ADS. (see 3.1). Feed, with an electrical length equal 180 degrees have been added to the network coupler. In this way, on the output phase was not changed relative to the input. Simulation was made in the frequency range from 1.5 GHz to 3.5 GHz for the line parameters described above.

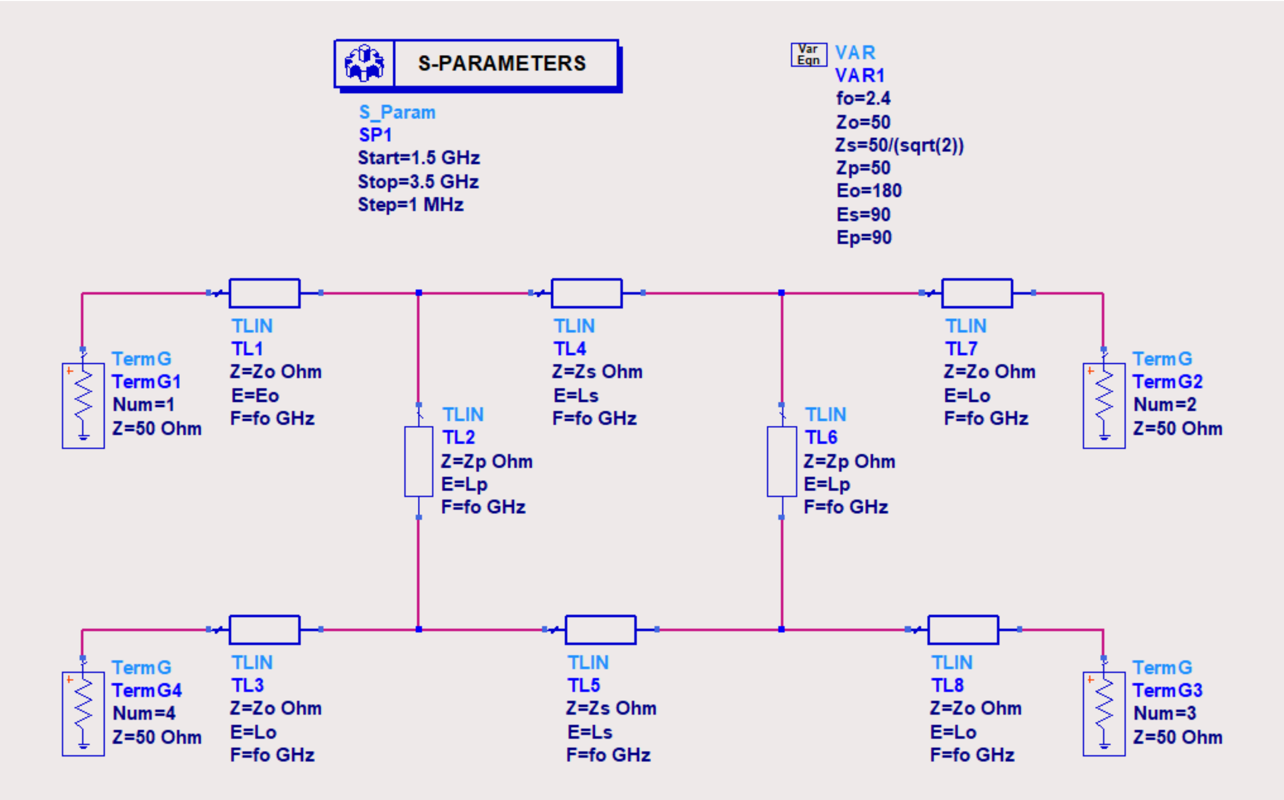


Figure 11: Coupler design in the form ideal line circuit schematic.

In the next step, the ideal transmission lines were changed for microstrip lines with real parameters. 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

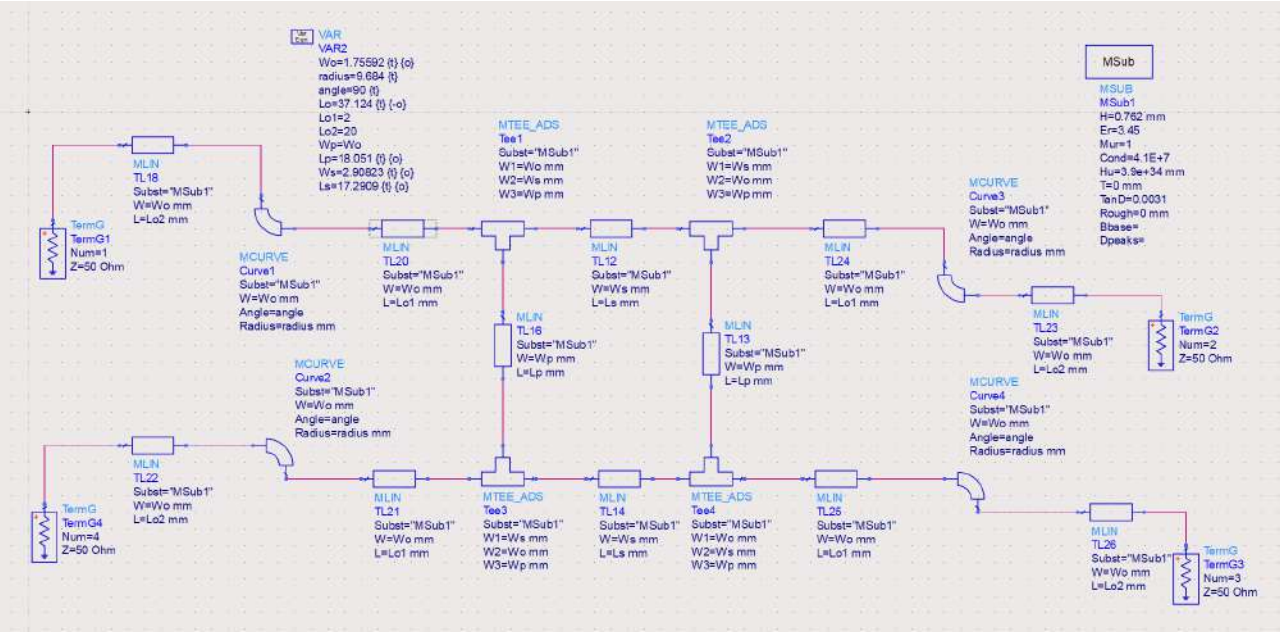


Figure 12: Network of circuits after changing the ideal line into a microstrip line with all dimensions.

An important feature of the branch coupler is the use of quarter-wave lines. The dimension of the feed line is much larger than the entire coupler, so we applied a round-shaped feed so that the whole structure has a square-like shape. In the further part of the work we planned to miniaturise the system by replacing quarter-wave sections with meandering line (shortening the physical length while maintaining the electrical length).

The next step was to draw the same project in InventSim and HFSS. When we were designing the coupler in InventSim, symmetry of the system was used.

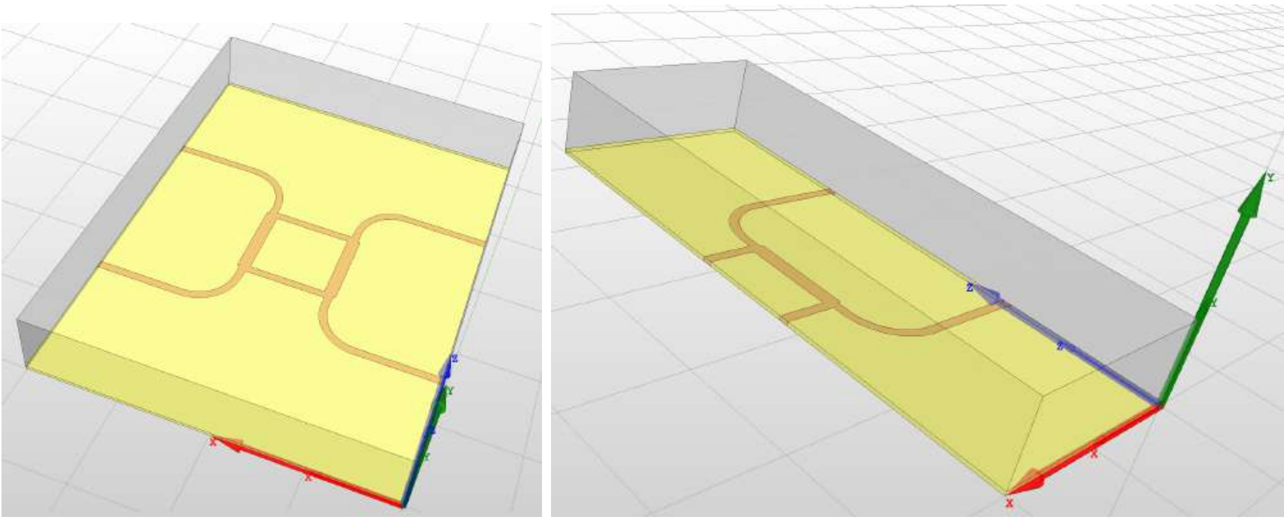


Figure 13: On the left the full structure of the coupler, on the right half.

3.4 Designed layout

For the designed coupler, a layout was generated, and then a simulation was carried out in Momentum.

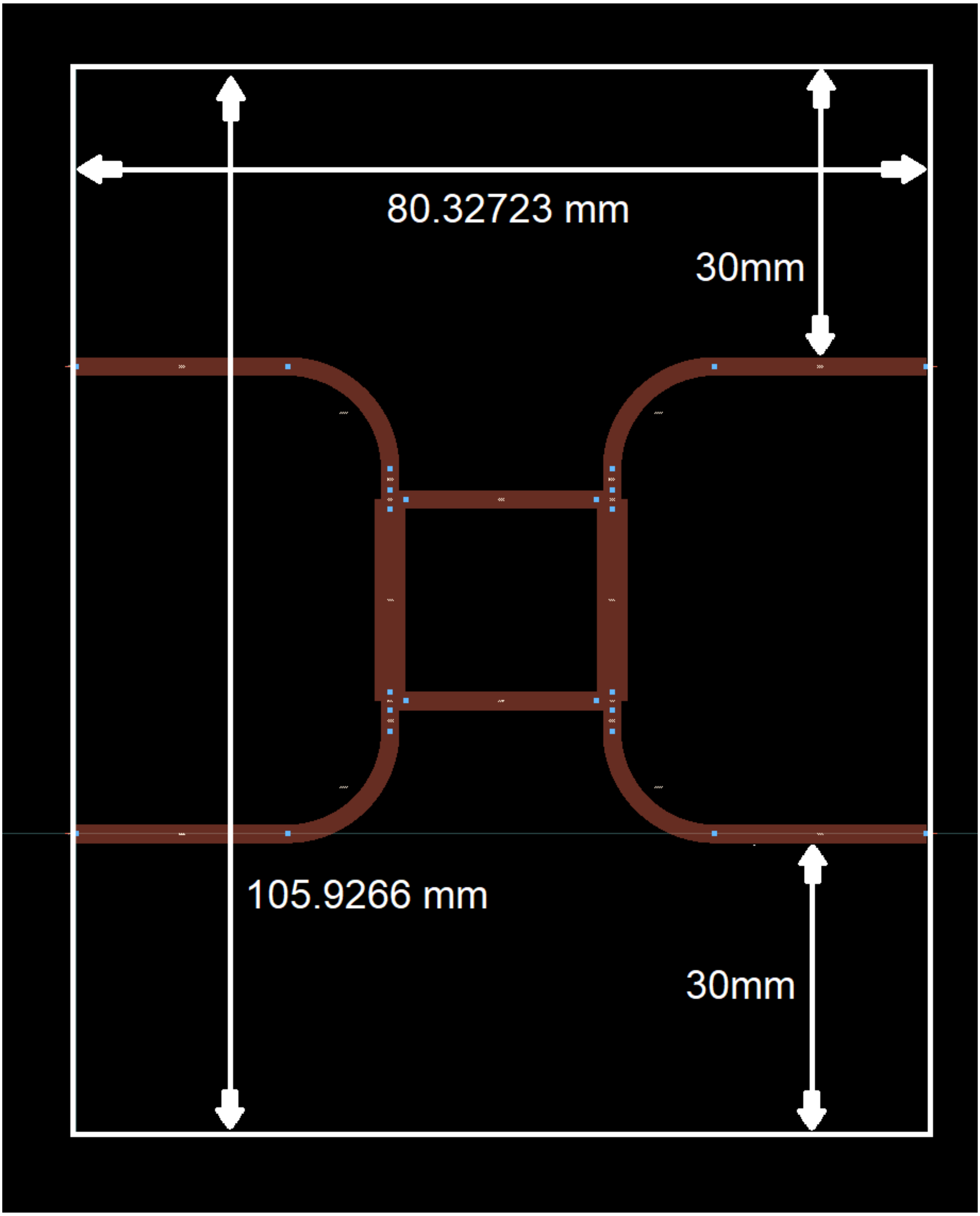
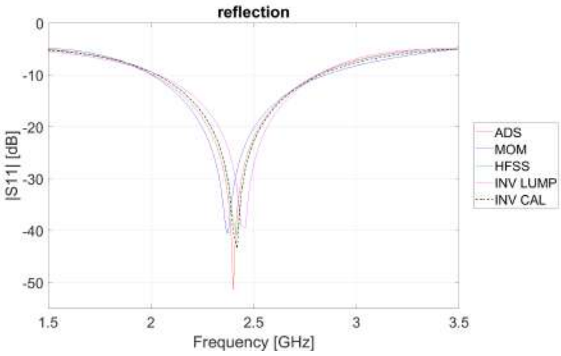
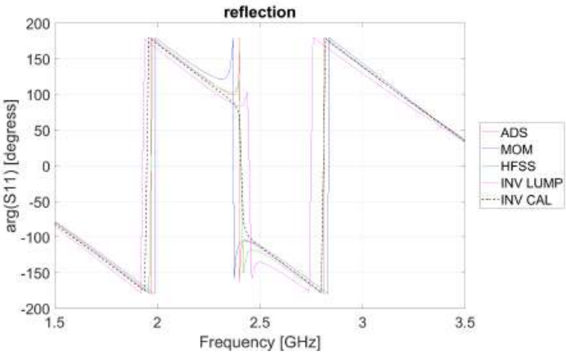


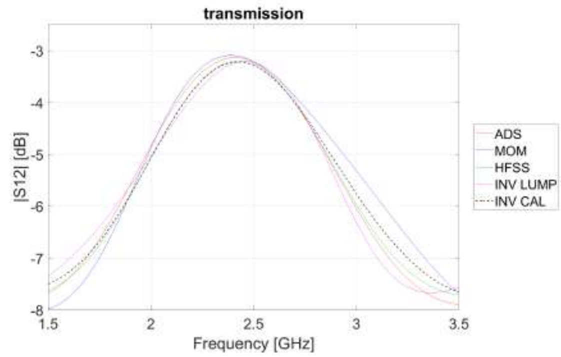
Figure 14: Dimension of PCB which was sent for implementation in a technological process.

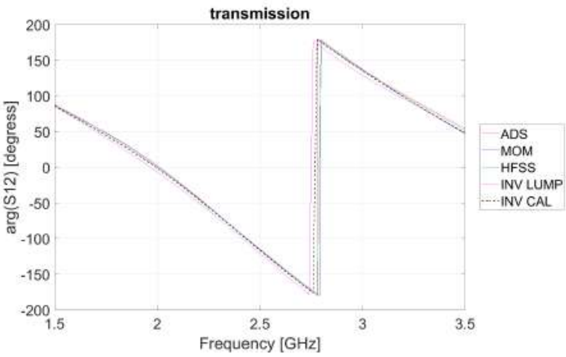
3.5 Simulation results - 3dB branch coupler

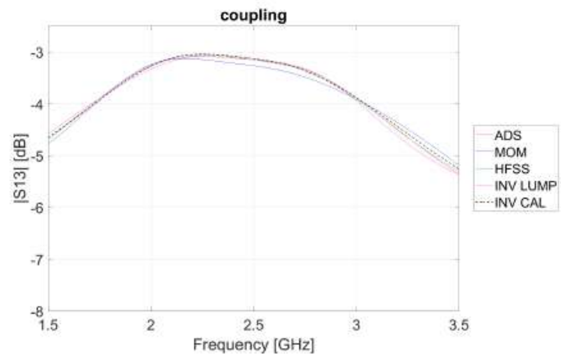
The results of simulation were separated due to its coupler basic parameters (resulting from the scattering matrix), reflection, transmission, isolation, coupling, assuming the reciprocity of the network.

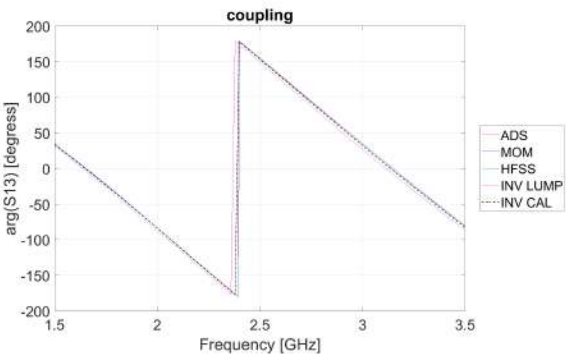


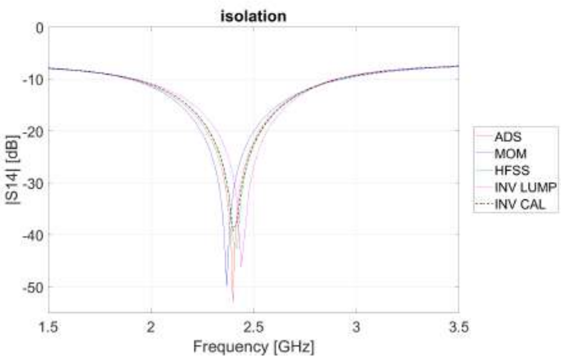


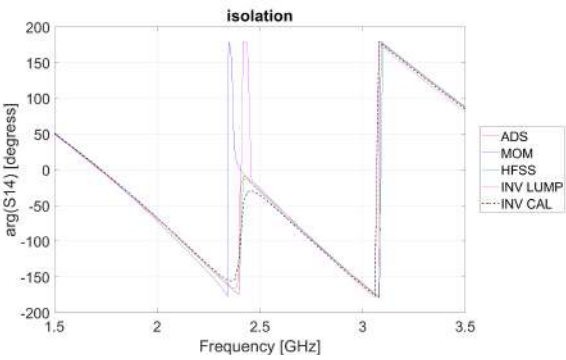








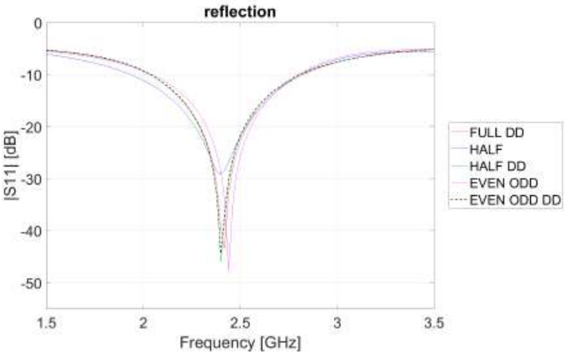


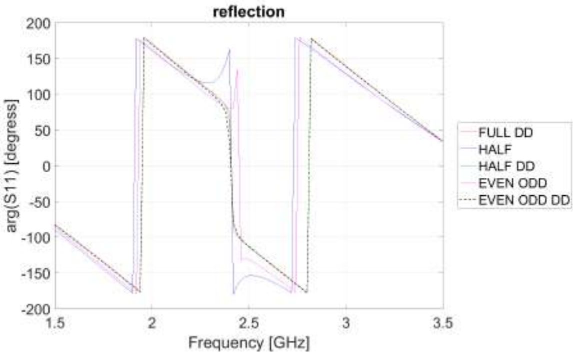


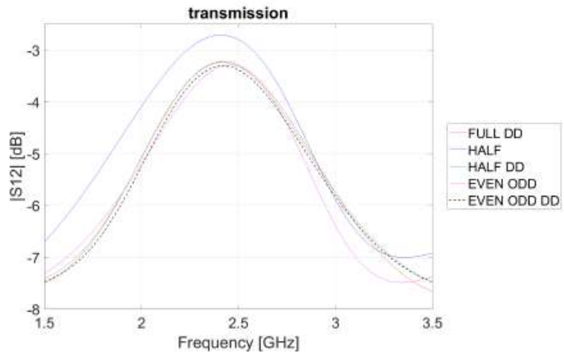
As you can see after calibration, results from InventSim are converging with the other simulators and the circuit model. The desired results of the coupling parameters were obtained.

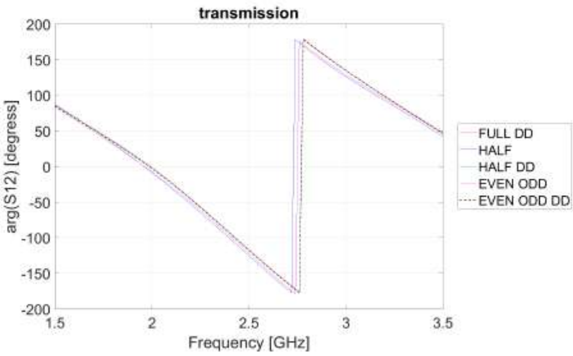
3.6 Structure symmetry, connection and even odd result

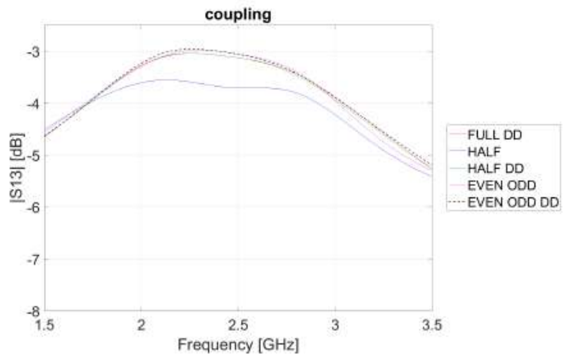
- FULL - simulation with ports the whole structure without "cutting" (lump port without calibration)
- HALF - the combination of two symmetrical four-ports, in effect four-ports come into being
- HALF DD - as above with the use of calibration Double Delay
- EVEN ODD - the combination of two symmetrical two-ports, simulated with a short and open at the intersection of the system (perfect electric and perfect magnetic wall) see equation(8).
- EVEN ODD DD - as above with the use of calibration Double Delay

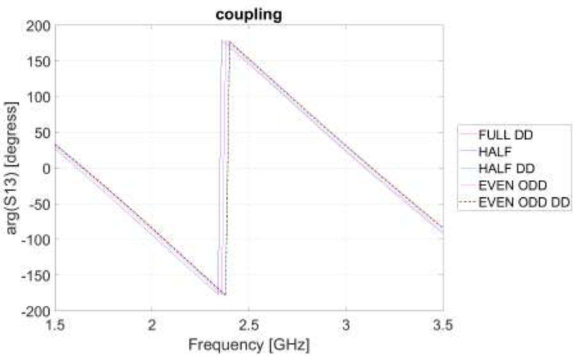


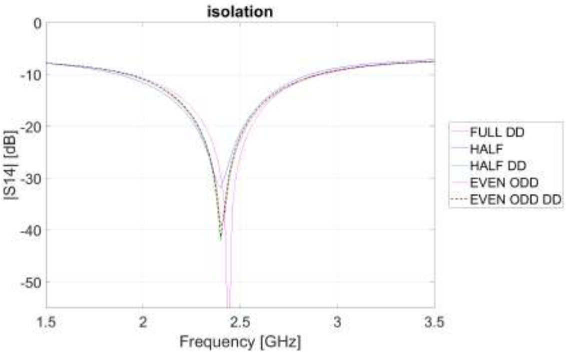


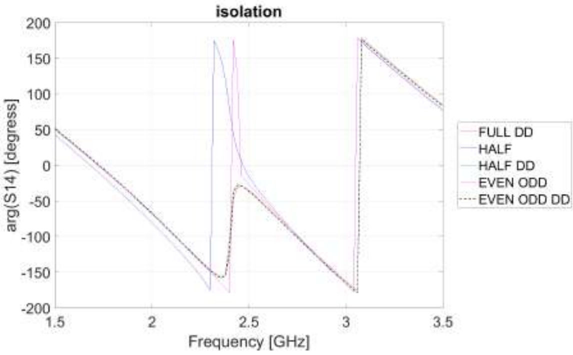












As you can see, after calibration the results coincide to the simulation of the whole structure however, without calibration the results are affected by an error. This error box has been removed in the de-embedding process

4 Conclusion

The design of the microstrip 3dB branch coupler was successful. The results of simulation shows that it is correct to use the calibration for designing systems using symmetry. Also even odd excitation analysis give convergent results.

Most of the master's diploma was completed, of the few tasks that have been left to print:

- miniaturization of the project coupler (e.g through the use of meander lines)
- realization and measurement of the system (experimental research)
- project verification by comparing simulation results with measurements

References

[1] Materials from the lecture on the design of passive microwave systems, http://mwave.eti.pg.gda.pl/

[2] David M. Pozar, Microwave Engineering, 4th Edition, Wiley, 2011

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[4] Wu, Q., Yang, Y., Lin, M., Shi, X. Miniaturized broadband branch-line coupler. Microwave and Optical Technology Letters, 2014