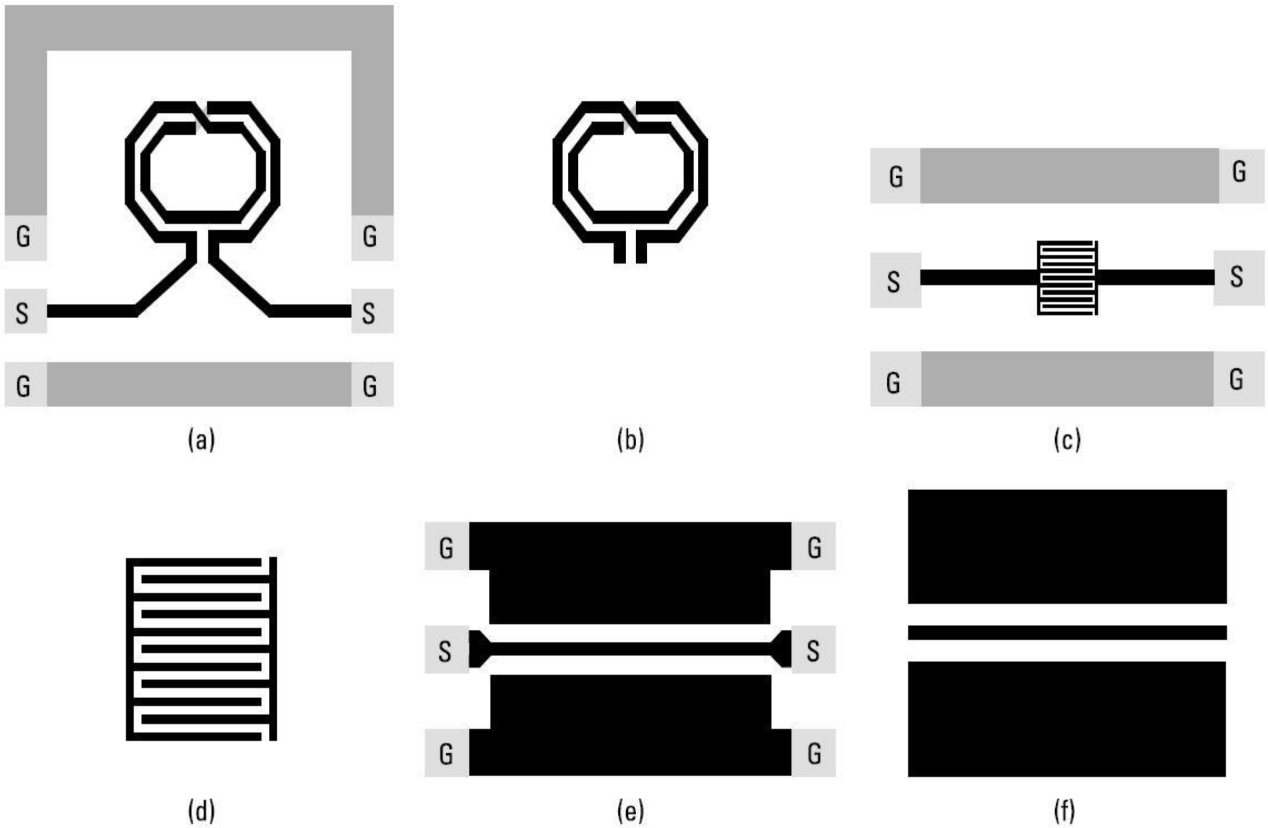
Introduction RAW Device

- Typically, the **RAW device** consists of the actual **device under test** (DUT) and some interconnecting structures such as feed lines and pads for on-wafer testing.



Ref: Errikos Lourandakis, On-Wafer Microwave Measurements and De-Embedding, 2016

Examples of RAW devices and DUTs for on-wafer characterization:

a) RAW Inductor

b) Inductor DUT

c) RAW MOM Capacitor

d) Capacitor DUT

e) RAW CPW T-line

f) CPW DUT

Introduction Even- and Odd-Mode Excitations(1)

- **Symmetrical four-port** networks are of particular interest since they **allow for analysis in terms of even- and odd-mode excitation.**

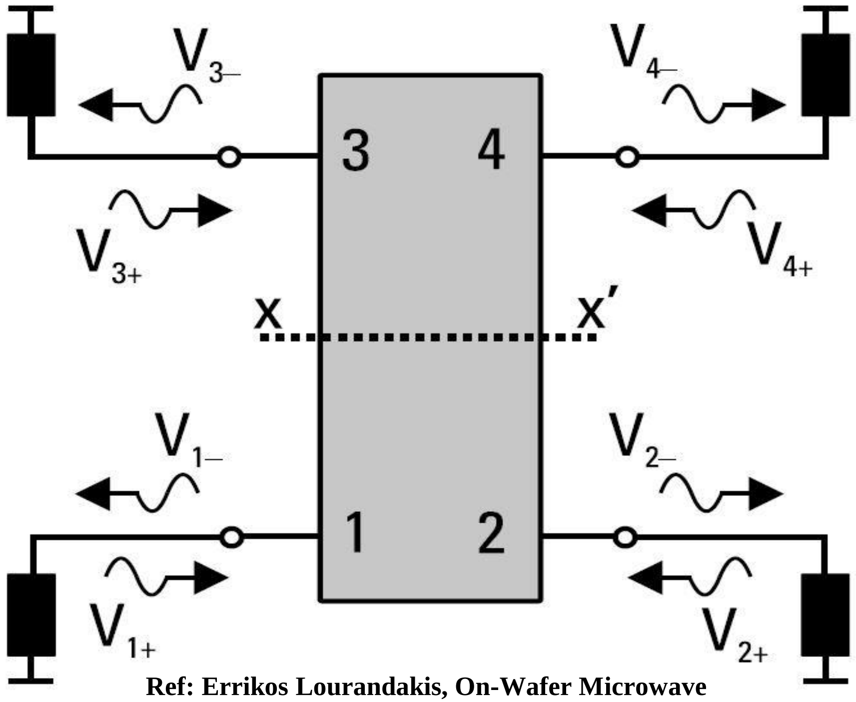
- Due to **symmetry** and the reciprocal nature of the network we may state that **$S_{ij} = S_{ji}$, where $i, j = 1 \cdots 4$ and $S_{11} = S_{33}$, $S_{22} = S_{44}$, $S_{34} = S_{12}$, and $S_{23} = S_{14}$**, which results in a compact S-parameter matrix representation.

$$\begin{bmatrix} V_1- \\ V_2- \\ V_3- \\ V_4- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \times \begin{bmatrix} V_1+ \\ V_2+ \\ V_3+ \\ V_4+ \end{bmatrix}$$

Symmetrical four-port

$$\begin{bmatrix} V_1- \\ V_2- \\ V_3- \\ V_4- \end{bmatrix} = \begin{bmatrix} [S_A] & [S_B] \\ [S_B] & [S_A] \end{bmatrix} \times \begin{bmatrix} V_1+ \\ V_2+ \\ V_3+ \\ V_4+ \end{bmatrix}$$

$$S_A = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}, \quad S_B = \begin{bmatrix} S_{31} & S_{14} \\ S_{41} & S_{42} \end{bmatrix}$$

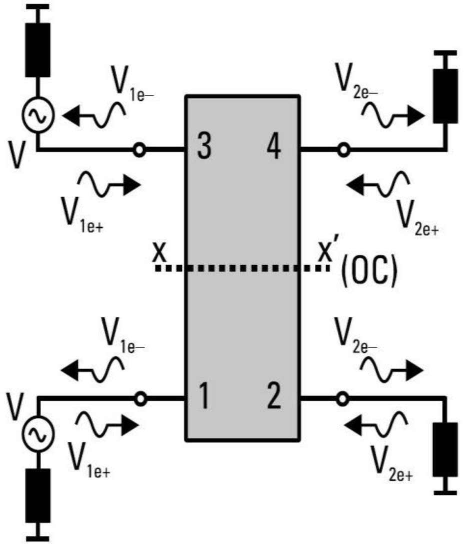


Ref: Errikos Lourandakis, On-Wafer Microwave Measurements and De-Embedding, 2016

Introduction Even- and Odd-Mode Excitations(2)

Even Mode

- The symmetry plane $x - x'$ corresponds now to an open-circuit (OC). Let $V_{1\pm} = V_{3\pm} = V_{1e\pm}$ and $V_{2\pm} = V_{4\pm} = V_{2e\pm}$ be the even-mode signals to be considered in the analysis.



$$\begin{bmatrix} V_{1e}- \\ V_{2e}- \\ V_{3e}- \\ V_{4e}- \end{bmatrix} = \begin{bmatrix} [S_A] & [S_B] \\ [S_B] & [S_A] \end{bmatrix} \times \begin{bmatrix} V_{1e}+ \\ V_{2e}+ \\ V_{3e}+ \\ V_{4e}+ \end{bmatrix}$$

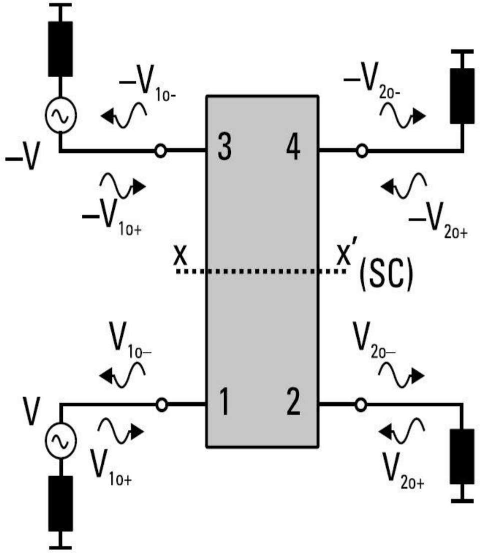
$$\begin{bmatrix} V_{1e}- \\ V_{2e}- \end{bmatrix} = ([S_A] + [S_B]) \times \begin{bmatrix} V_{1e}+ \\ V_{2e}+ \end{bmatrix}$$

Even-mode excitation for symmetric four-port network.

$$\begin{cases} \begin{bmatrix} V_{1e}- \\ V_{2e}- \end{bmatrix} = [S_e] \times \begin{bmatrix} V_{1e}+ \\ V_{2e}+ \end{bmatrix} \\ [S_e] = [S_A] + [S_B] \\ [S_A] = \dfrac{[S_e] + [S_o]}{2} \\ [S_B] = \dfrac{[S_e] - [S_o]}{2} \end{cases}$$

Odd Mode

- The corresponding odd-mode excitation scheme with $V_{1\pm} = -V_{3\pm} = V_{1o\pm}$ and $V_{2\pm} = -V_{4\pm} = V_{2o\pm}$ and its short-circuit (SC) symmetry plane $x - x'$.



$$\begin{bmatrix} V_{1o}- \\ V_{2o}- \\ -V_{3o}- \\ -V_{4o}- \end{bmatrix} = \begin{bmatrix} [S_A] & [S_B] \\ [S_B] & [S_A] \end{bmatrix} \times \begin{bmatrix} V_{1o}+ \\ V_{2o}+ \\ -V_{3o}+ \\ -V_{4o}+ \end{bmatrix}$$

$$\begin{bmatrix} V_{1o}- \\ V_{2o}- \end{bmatrix} = ([S_A] - [S_B]) \times \begin{bmatrix} V_{1o}+ \\ V_{2o}+ \end{bmatrix}$$

Odd-mode excitation for symmetric four-port network.

$$\begin{cases} \begin{bmatrix} V_{1o}- \\ V_{2o}- \end{bmatrix} = [S_o] \times \begin{bmatrix} V_{1o}+ \\ V_{2o}+ \end{bmatrix} \\ [S_o] = [S_A] - [S_B] \\ [S_A] = \dfrac{[S_e] + [S_o]}{2} \\ [S_B] = \dfrac{[S_e] - [S_o]}{2} \end{cases}$$

Ref: Errikos Lourandakis, On-Wafer Microwave Measurements and De-Embedding, 2016

Introduction Even- and Odd-Mode Excitations(3)

$$S_e = \begin{bmatrix} S_{11e} & S_{12e} \\ S_{21e} & S_{22e} \end{bmatrix}$$

$$S_o = \begin{bmatrix} S_{11o} & S_{12o} \\ S_{21o} & S_{22o} \end{bmatrix}$$

$$S_A = \begin{bmatrix} \frac{S_e + S_o}{2} & \frac{S_e + S_o}{2} \\ \frac{S_e + S_o}{2} & \frac{S_e + S_o}{2} \end{bmatrix}$$

$$S_B = \begin{bmatrix} \frac{S_e - S_o}{2} & \frac{S_e - S_o}{2} \\ \frac{S_e - S_o}{2} & \frac{S_e - S_o}{2} \end{bmatrix}$$

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

$$S_{11} = S_{33} = \frac{S_{11e} + S_{11o}}{2}$$

$$S_{12} = S_{21} = S_{34} = S_{43} = \frac{S_{21e} + S_{21o}}{2}$$

$$S_{13} = S_{31} = \frac{S_{11e} - S_{11o}}{2}$$

$$S_{14} = S_{41} = S_{32} = S_{23} = \frac{S_{21e} - S_{21o}}{2}$$

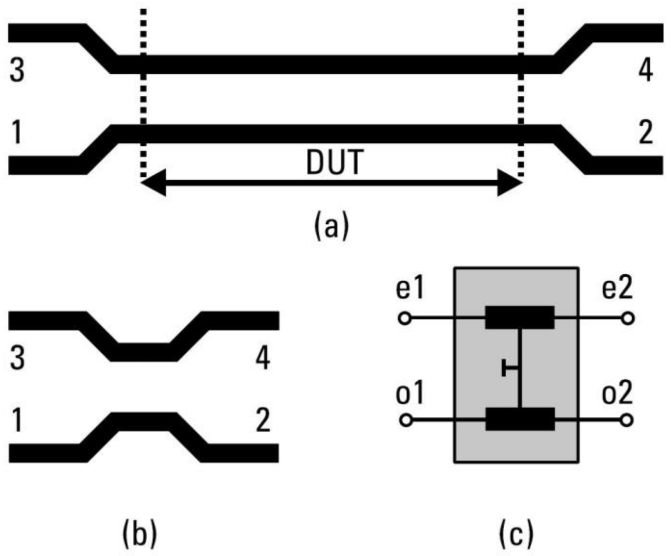
$$S_{22} = S_{44} = \frac{S_{22e} + S_{22o}}{2}$$

$$S_{24} = S_{42} = \frac{S_{22e} - S_{22o}}{2}$$

- At this point we have reconstructed the complete four-port S-parameter network matrix by performing an even- and odd-mode analysis and exploring the network symmetry.
- This technique is not universally applicable to a generic four-port network since it assumes the aforementioned symmetry condition.
- Fortunately enough, this type of symmetry is encountered in many microwave networks such as couplers, filters and differential signal routings.

Thru De-embedding Four Port RAW Device

- In the case of four-port networks with an even- and odd-mode symmetry, as shown by plane *x* – *x*, the S-parameter matrix of the four-port network can be transformed into a block diagonal representation with two independent two-port networks.
- By adopting this convention, we end up with an even-mode two-port network with terminals e_1, e_2 and an odd-mode two-port network with corresponding terminals o_1, o_2.



Symmetrical four-port network and THRU device.

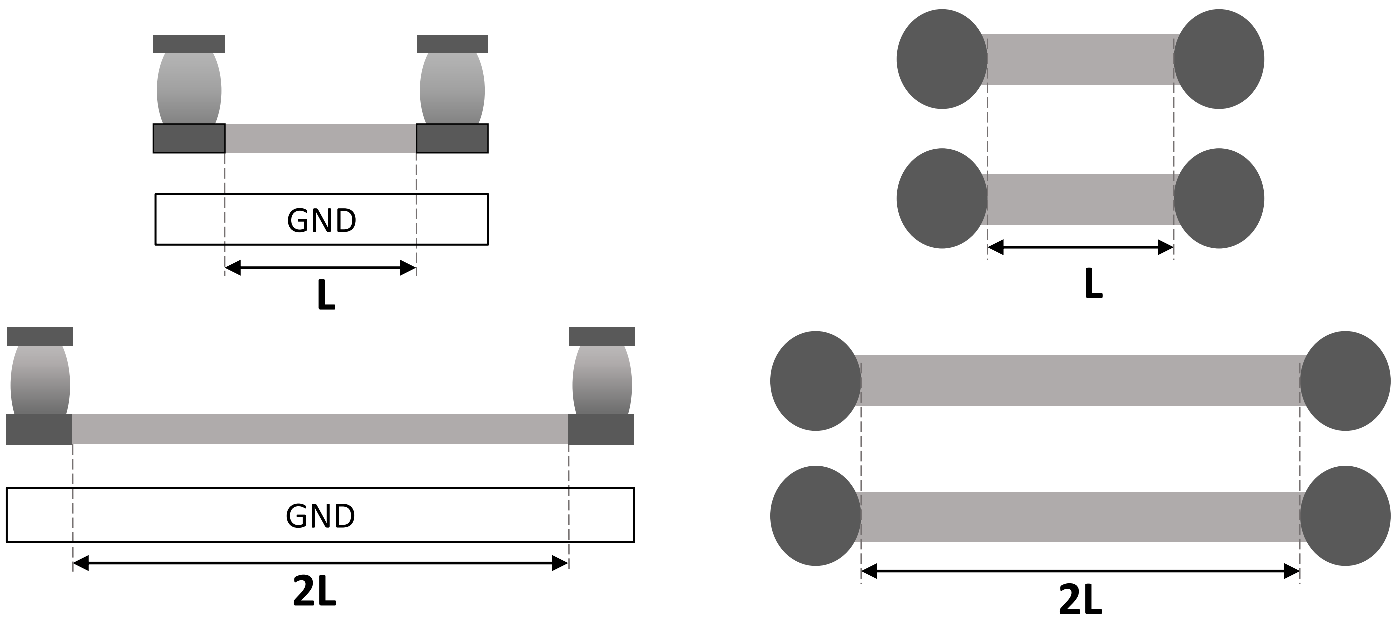
a) Four-port RAW device
b) Four-port THRU device
c) uncoupled two-ports.

$$T_{eeRAW} = T_{eeLEFT} \times T_{eeDUT} \times T_{eeRIGHT}$$

$$T_{ooRAW} = T_{ooLEFT} \times T_{ooDUT} \times T_{ooRIGHT}$$

Ref: Errikos Lourandakis, On-Wafer Microwave Measurements and De-Embedding, 2016

L-2L De-embedding Four Port RAW Device



$$ABCD_{meas\_L} = ABCD_{LS} * ABCD_{L} * ABCD_{RS}$$

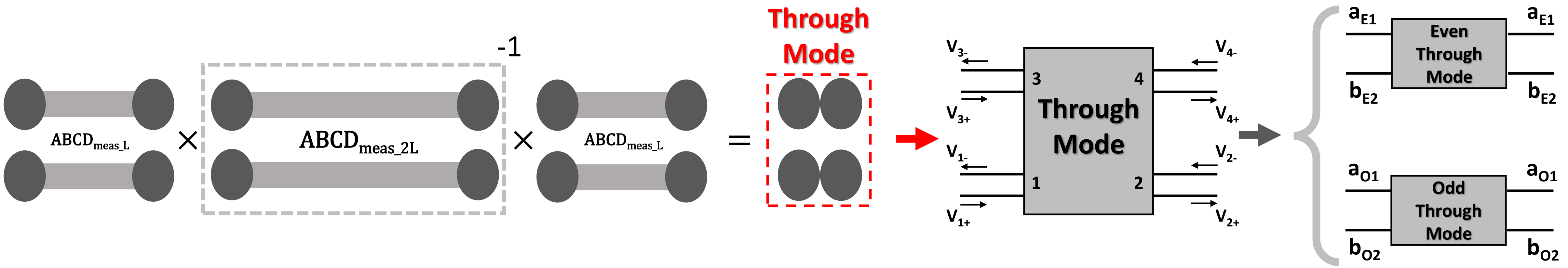
$$ABCD_{meas\_2L} = ABCD_{LS} * ABCD_{2L} * ABCD_{RS}$$

Where,

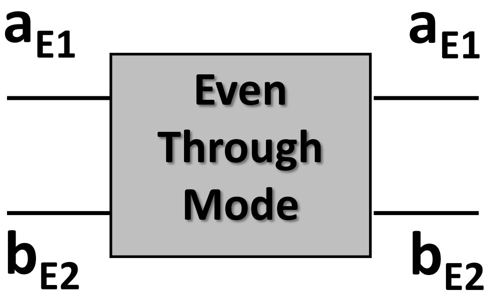
$ABCD_{LS}$: Represent the matrix of the left **Bump+Pads**;

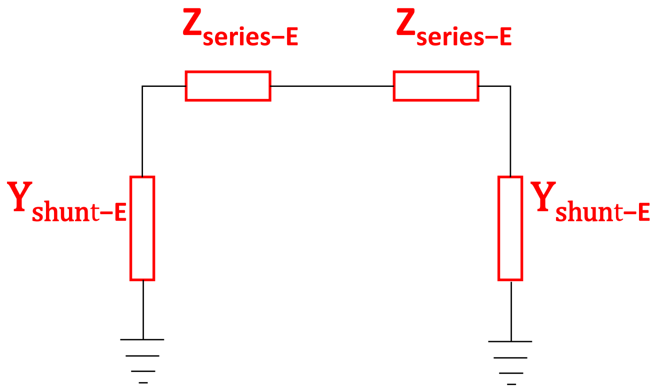
$ABCD_{L\&2L}$: Represent the matrix of the **lines**;

$ABCD_{RS}$: Represent the matrix of the right **Bump+Pads**;



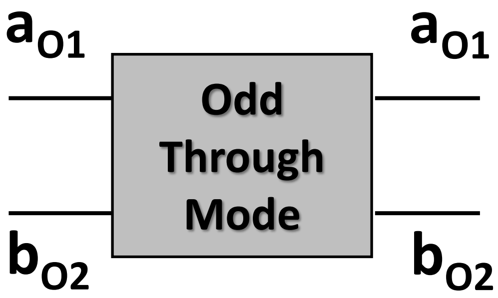
L-2L De-embedding Four Port RAW Device

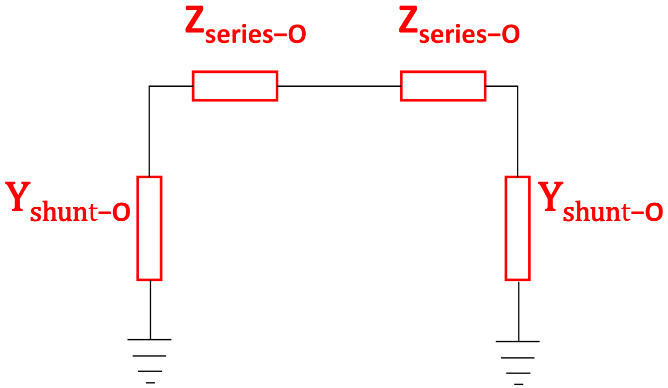




$$\begin{bmatrix} 2Y_{shunt-E}Z_{series-E}+1 & 2Z_{series-E} \\ 2Y_{shunt}(Y_{shunt-E}Z_{series-E}+1) & 2Y_{shunt-E}Z_{series-E}+1 \end{bmatrix}$$

$$ABCD_{LS}=\begin{bmatrix} 1 & Z_{series-E} \\ Y_{shunt-E} & Y_{shunt-E}Z_{series-E}+1 \end{bmatrix},\quad ABCD_{RS}=\begin{bmatrix} Y_{shunt-E}Z_{series-E}+1 & Z_{series-E} \\ Y_{shunt-E} & 1 \end{bmatrix}$$

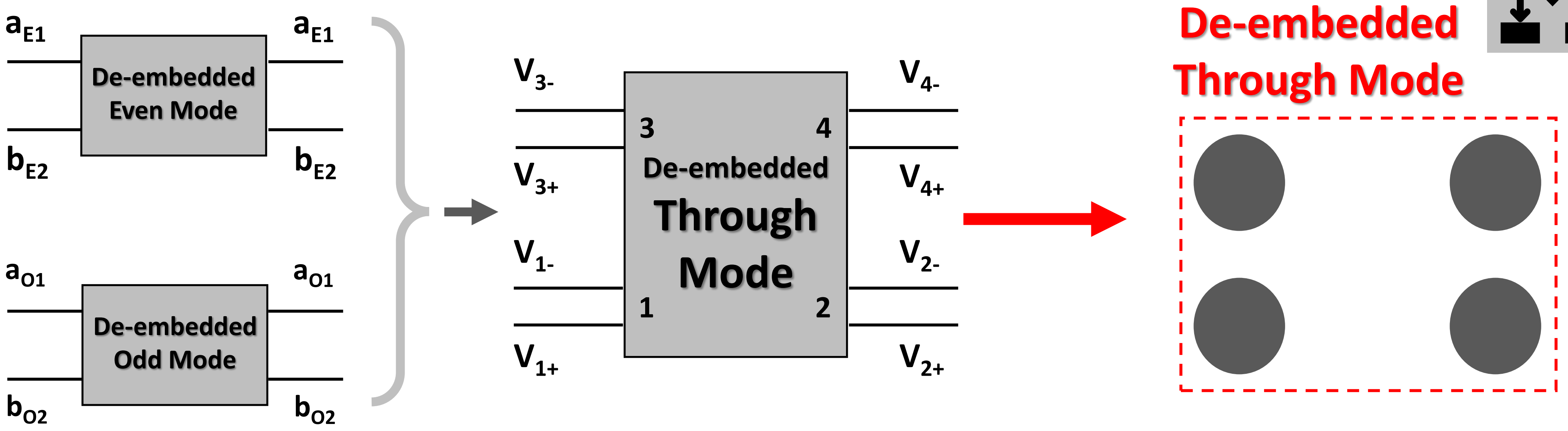




$$\begin{bmatrix} 2Y_{shunt-O}Z_{series-O}+1 & 2Z_{series-O} \\ 2Y_{shunt-O}(Y_{shunt-O}Z_{series-O}+1) & 2Y_{shunt-O}Z_{series-O}+1 \end{bmatrix}$$

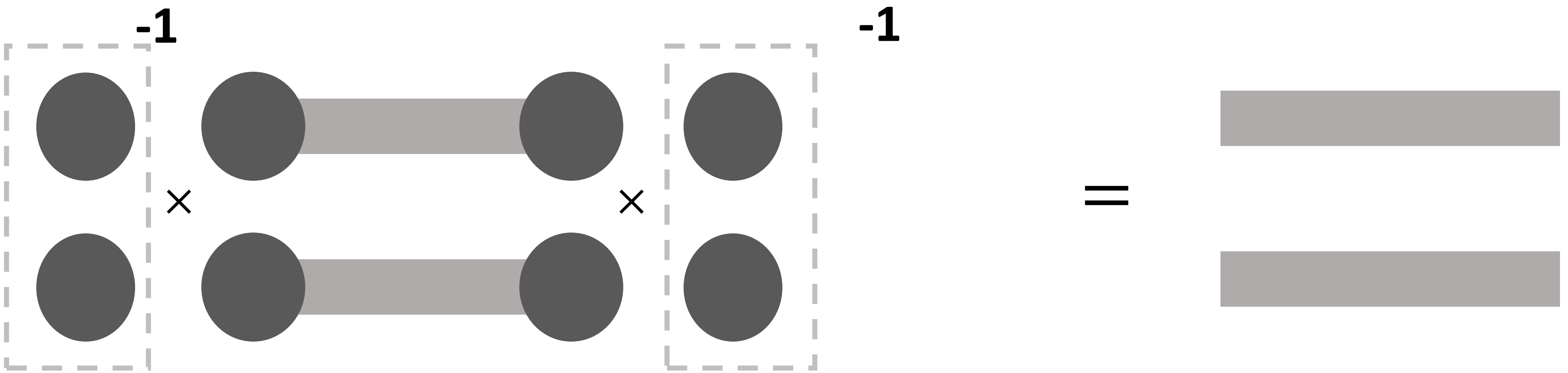
$$ABCD_{LS}=\begin{bmatrix} 1 & Z_{series-O} \\ Y_{shunt-O} & Y_{shunt-O}Z_{series-O}+1 \end{bmatrix},\quad ABCD_{RS}=\begin{bmatrix} Y_{shunt-O}Z_{series-O}+1 & Z_{series-O} \\ Y_{shunt-O} & 1 \end{bmatrix}$$

L-2L De-embedding Four Port RAW Device



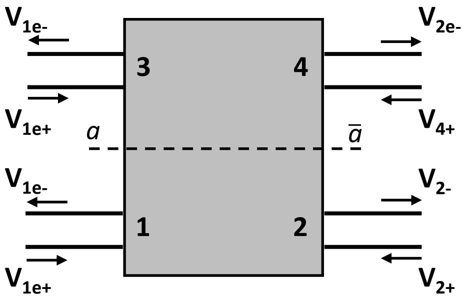
$$\mathbf{ABCD_L} = \mathrm{ABCD_{LS}}^{-1} * \mathrm{ABCD_{meas\_L}} * \mathrm{ABCD_{RS}}^{-1}$$

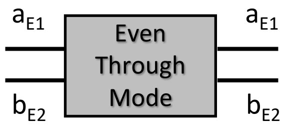
$$\mathbf{ABCD_{2L}} = \mathrm{ABCD_{LS}}^{-1} * \mathrm{ABCD_{meas\_2L}} * \mathrm{ABCD_{RS}}^{-1}$$



References

Through Mode





S_{thru}