Adapted from notes by
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ECE 5317-6351
Microwave Engineering

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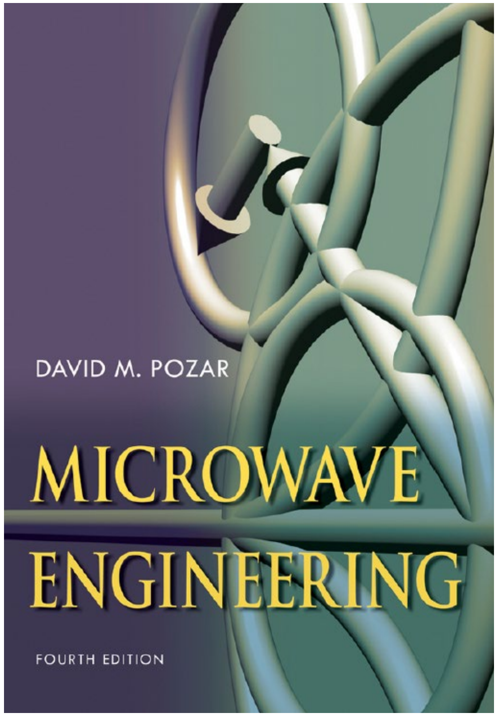
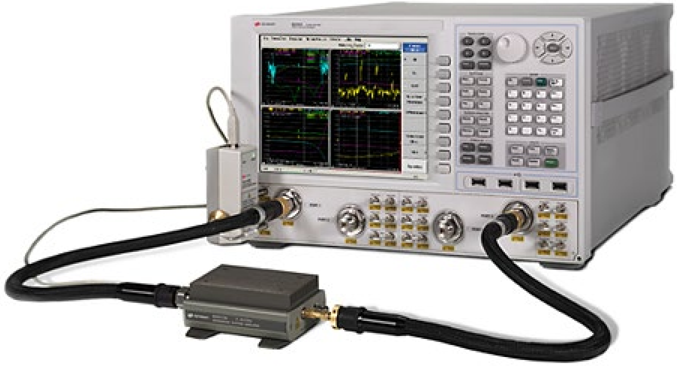
Dept. of ECE



Notes 17

S-Parameter Measurements



S-Parameter Measurements

S-parameters are typically measured, at microwave frequencies, with a network analyzer (NA).

These instruments have found wide, almost universal, application since the mid to late 1970's.

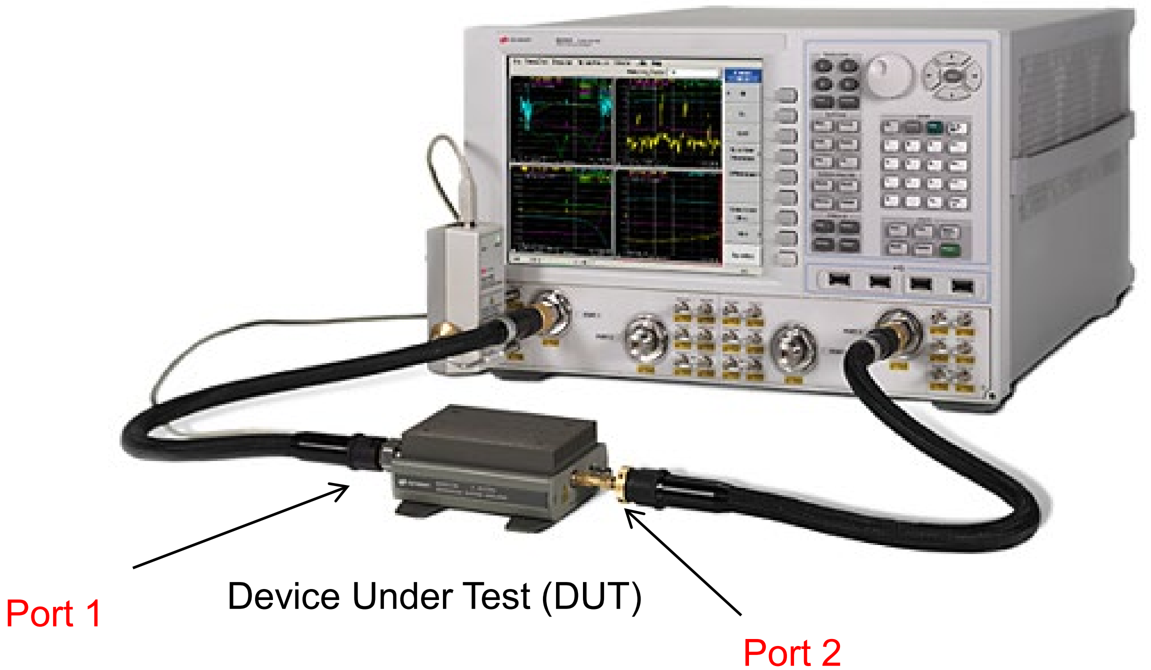
- Vector* network analyzer: Magnitudes and phases of the S parameters are measured.
- Scalar network analyzer: Only the magnitudes of the S-parameters are measured.

Most NA's measure 2-port parameters. Some measure 4 and 6 ports.

* The S parameters are really complex numbers, not vectors, but this is the customary name. There is an analogy between complex numbers and 2D vectors.

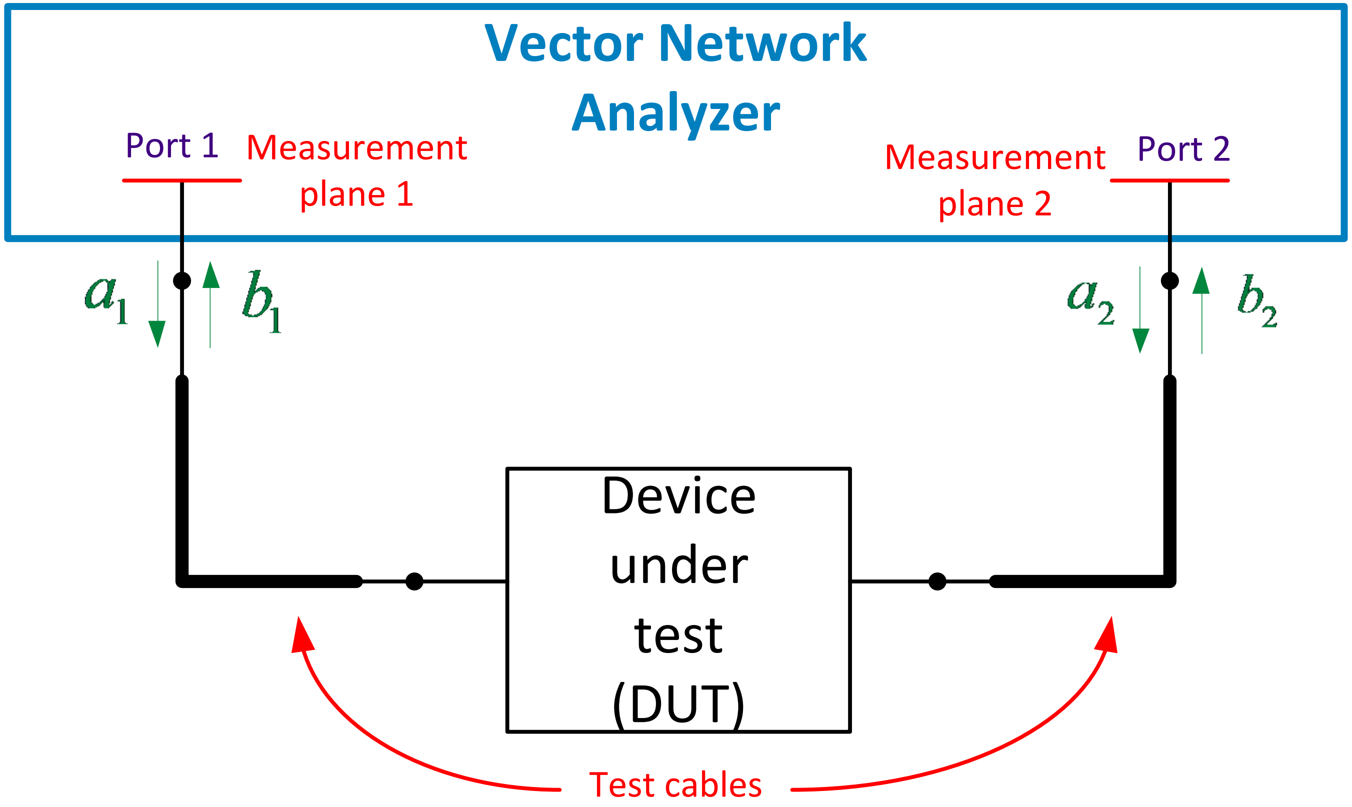
S-Parameter Measurements (cont.)

A Vector Network Analyzer (VNA) is usually used to measure *S* parameters.

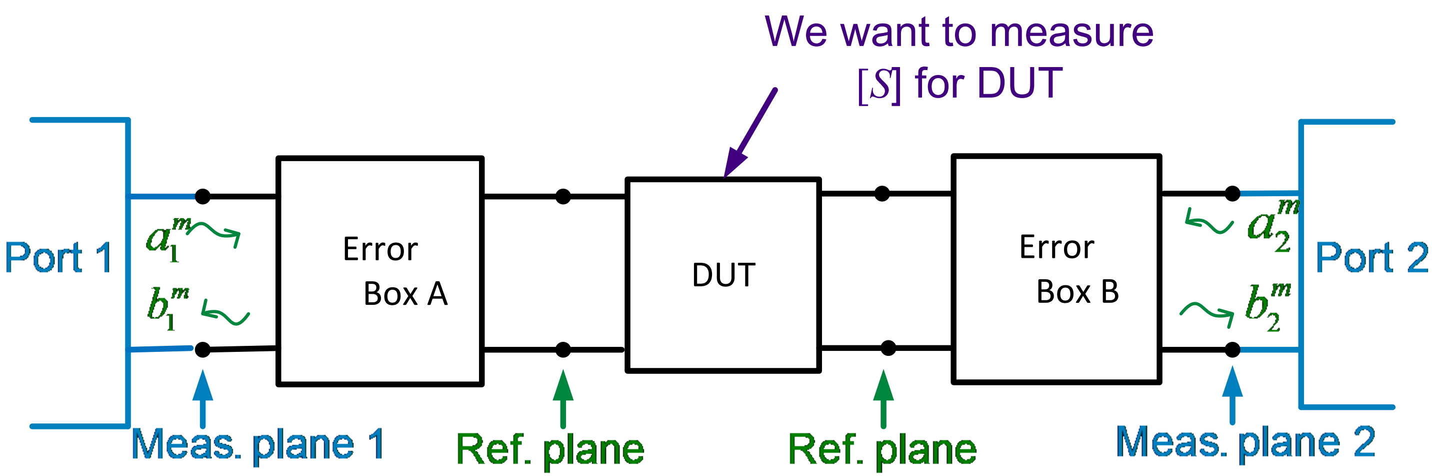


Note:
If there are more than 2 ports, we measure different pairs of ports separately with a 2-port VNA.

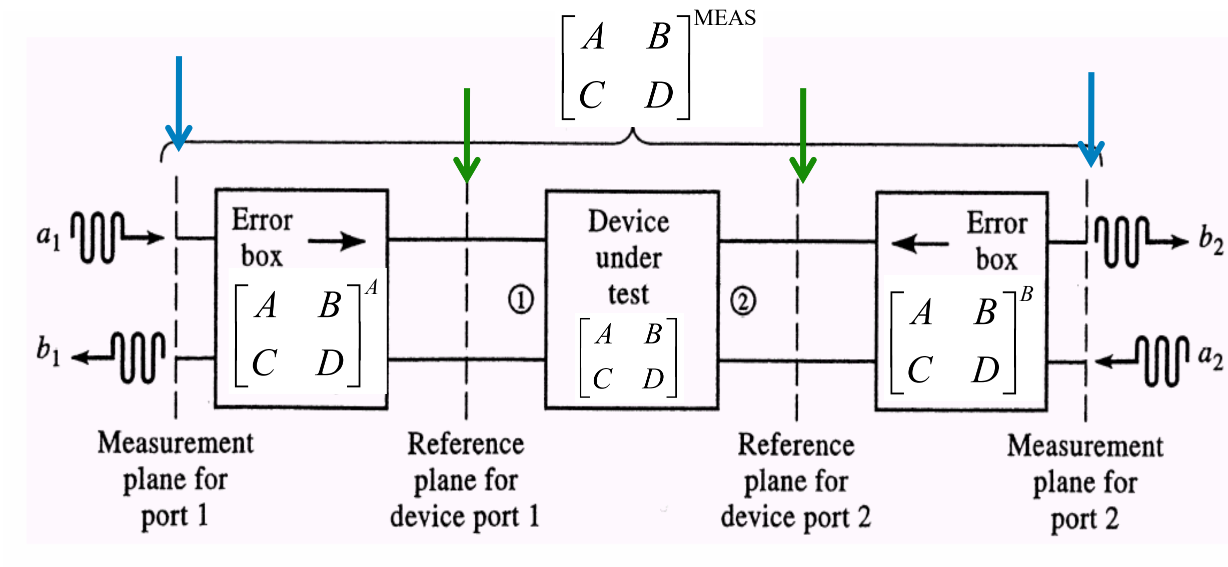
S-Parameter Measurements (cont.)



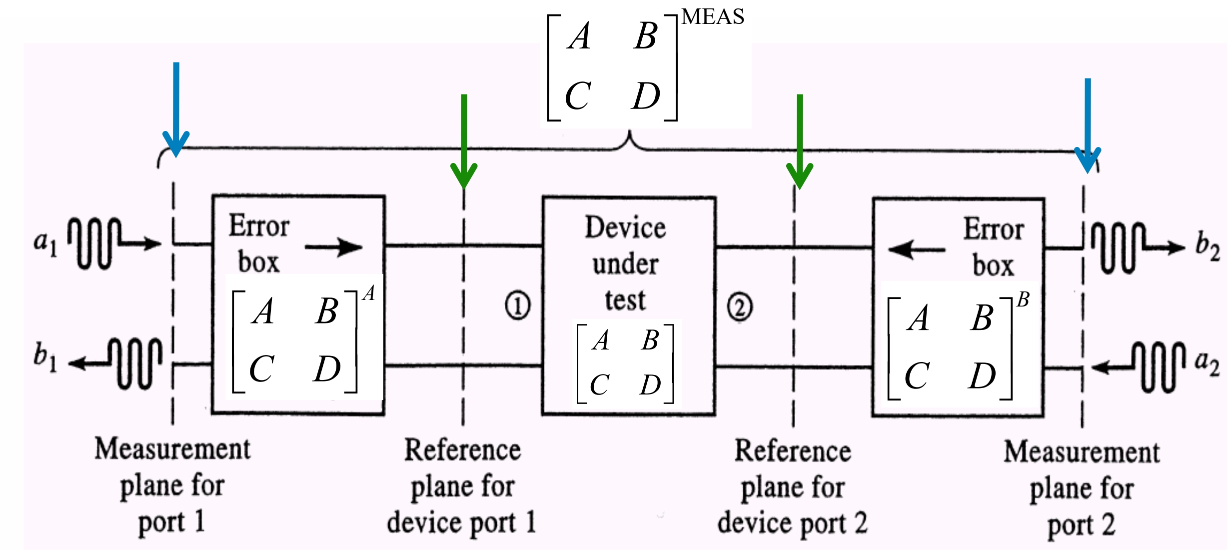
S-Parameter Measurements (cont.)



Error boxes contain effects
of test cables, connectors, couplers,…



S-Parameter Measurements (cont.)



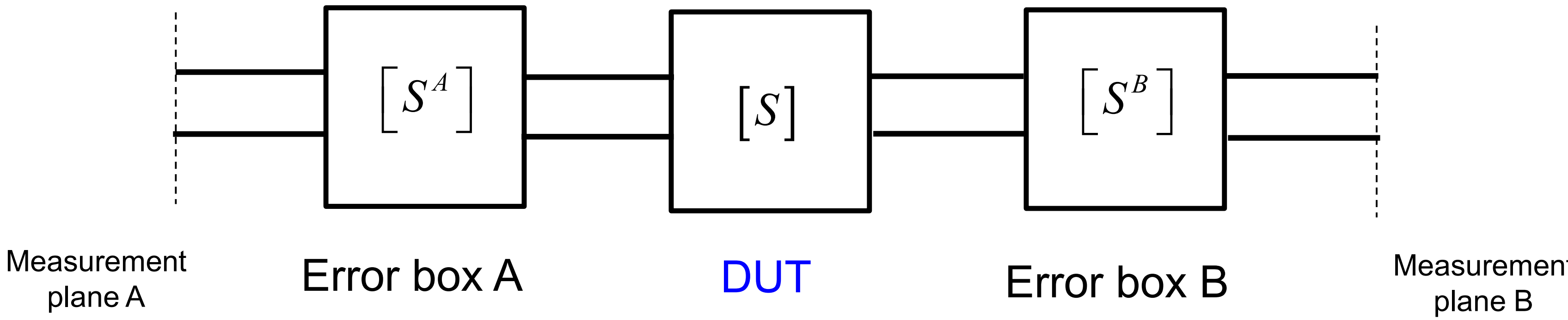
$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}^{\text{MEAS}} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{A} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{B}$$

Embedded inside measured ABCD matrix

De-embedded

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \left(\begin{bmatrix} A & B \\ C & D \end{bmatrix}^{A} \right)^{-1} \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{\text{MEAS}} \left(\begin{bmatrix} A & B \\ C & D \end{bmatrix}^{B} \right)^{-1}$$

S-Parameter Measurements (cont.)



Assume error boxes are reciprocal (symmetric matrices)

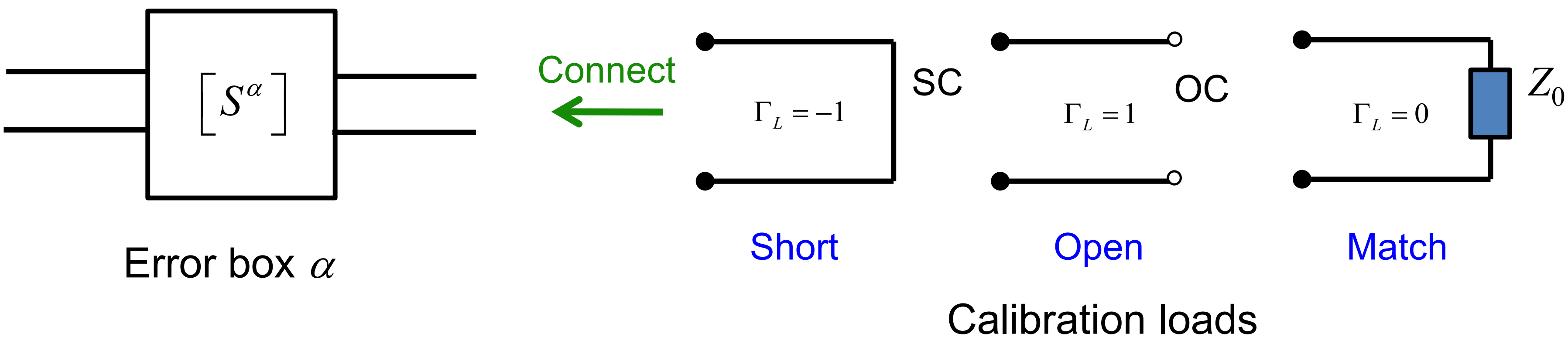
We need to "calibrate" to find $[S^A]$ and $[S^B]$.

If $[S^A]$ and $[S^B]$ are known $\Rightarrow$ we can extract $[S]$ from measurements.

This is called “de-embedding”.

Calibration

"Short, open, match" calibration procedure



These loads are connected to the end of the cable from the VNA.

$$S^m_{11_{SC}} = S^{\alpha}_{11} - \frac{\left(S^{\alpha}_{21}\right)^2}{1 + S^{\alpha}_{22}}$$

$$S^m_{11_{OC}} = S^{\alpha}_{11} + \frac{\left(S^{\alpha}_{21}\right)^2}{1 - S^{\alpha}_{22}}$$

$$S^m_{11_{match}} = S^{\alpha}_{11}$$

3 measurements:

$$\left(S^m_{11_{SC}}, S^m_{11_{OC}}, S^m_{11_{match}}\right)$$

3 unknowns:

$$\left(S^{\alpha}_{11}, S^{\alpha}_{21}, S^{\alpha}_{22}\right)$$

Recall from Notes 16:

$$\Gamma_{in} = S_{11} + \frac{S_{21} S_{12} \Gamma_L}{1 - \Gamma_L S_{22}}$$

Calibration (cont.)

“Thru-Reflect-Line (TRL)” calibration procedure

This is an improved calibration method that involves three types of connections:

1) The “thru” connection, in which port 1 is directly connected to port 2.
2) The “reflect” connection, in which a load with an (ideally) large (but not necessarily precisely known) reflection coefficient is connected.
3) The “line” connection, in which a length of matched transmission line (with an unknown length) is connected between ports 1 and 2.

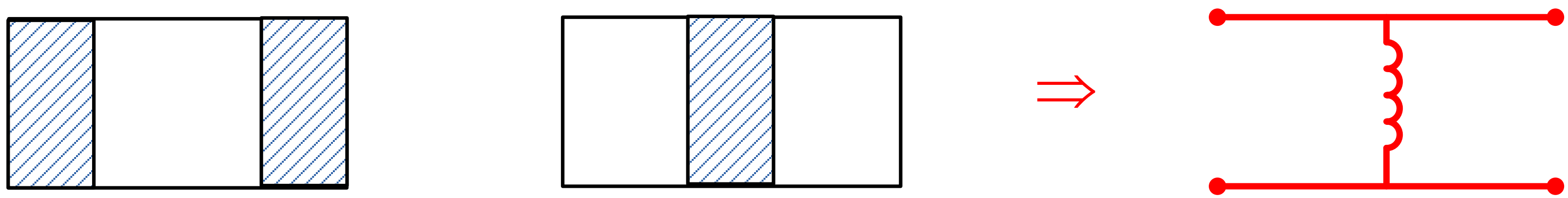
The advantage of the TRL calibration is that is does not require precise short, open, and matched loads.

This method is discussed in the Pozar book (pp. 193-196).

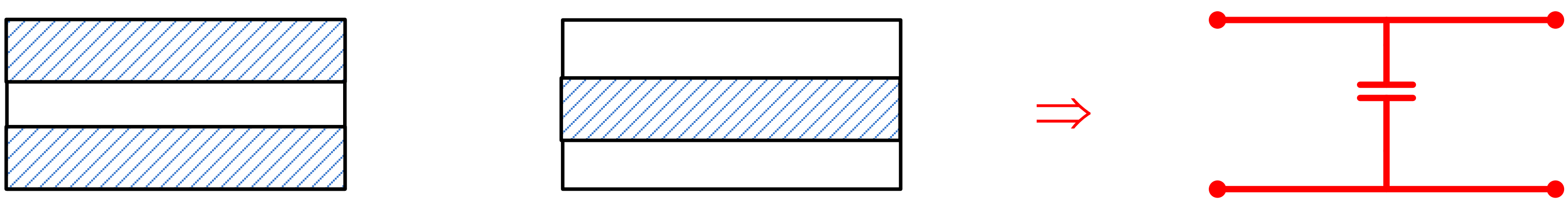
Discontinuities

- In microwave engineering, discontinuities are often represented by pi or tee networks.
- Sometimes the pi or tee network reduces to a singe series or shunt element.
- For waveguide systems, the TEN is used to represent the waveguide.

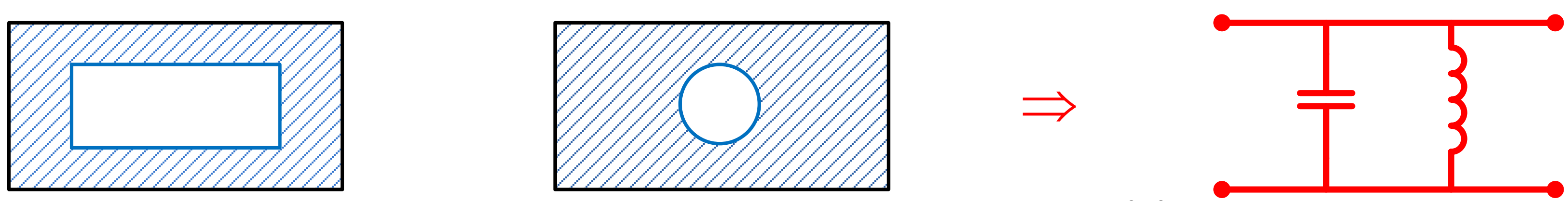
Discontinuities: Rectangular Waveguide



Inductive iris or strip

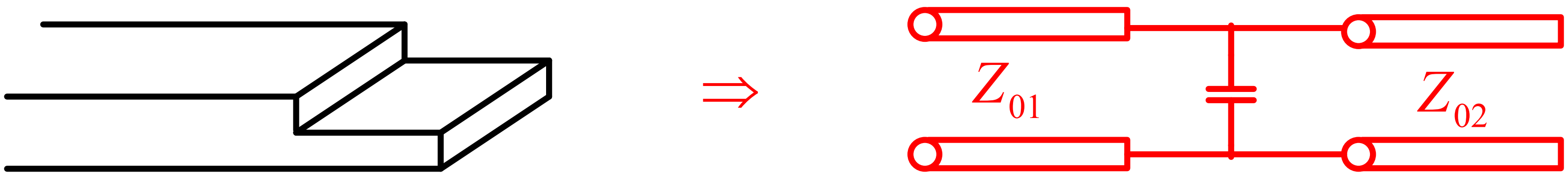


Capacitive iris or strip



Resonant iris

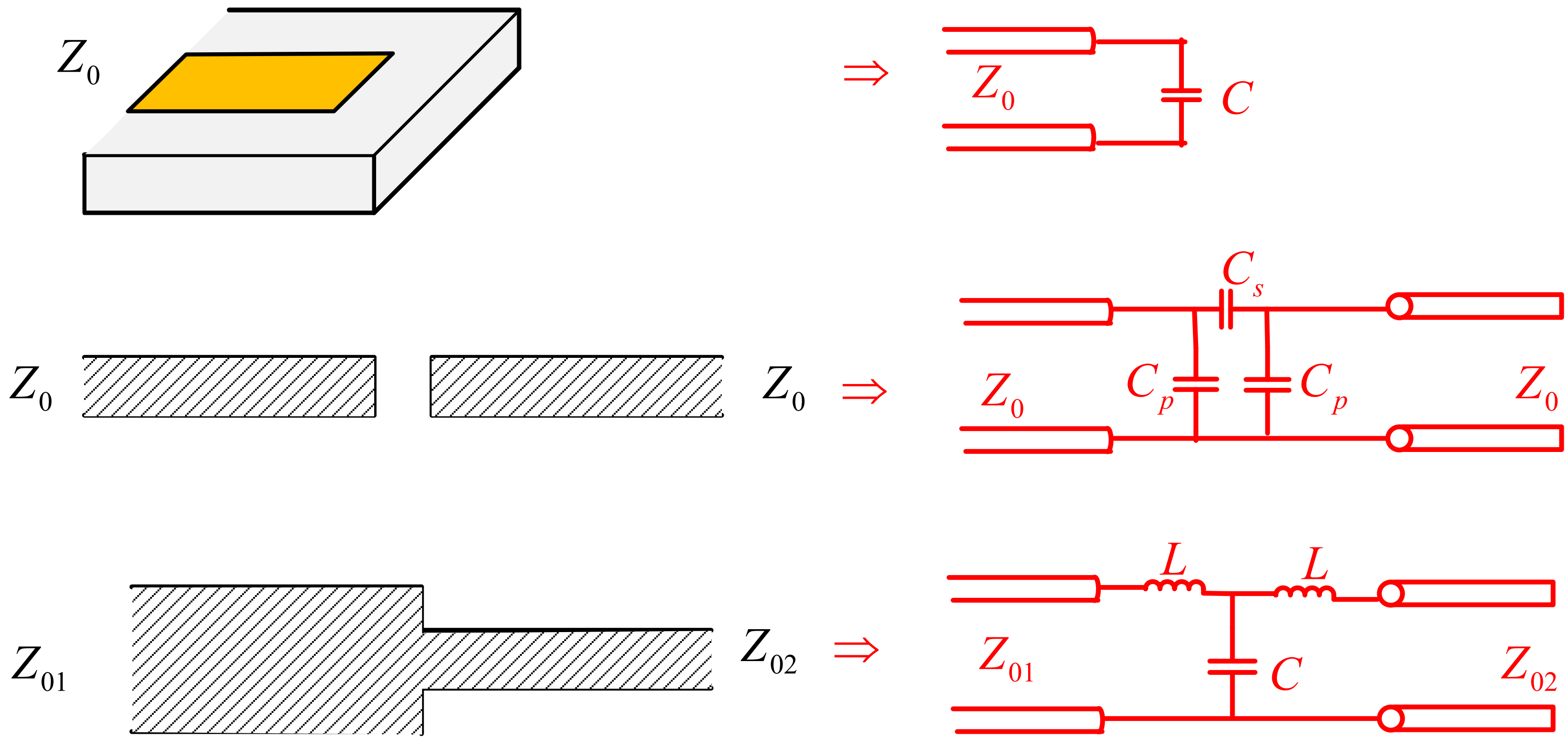
Discontinuities: RWG (cont.)



E plane step

H plane step

Discontinuities: Microstrip

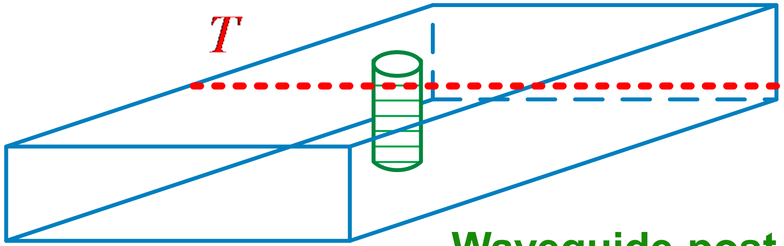


Note:
For a good equivalent circuit,
the element values are fairly stable over a wide range of frequencies.

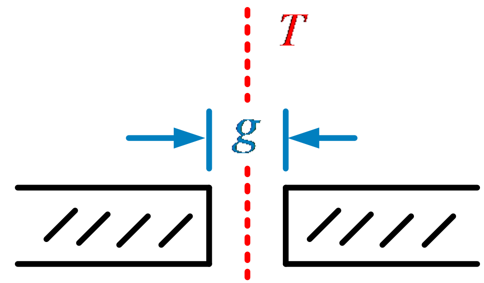
Z-Parameter Extraction

Assume a reciprocal and symmetrical waveguide or transmission-line discontinuity.

Examples



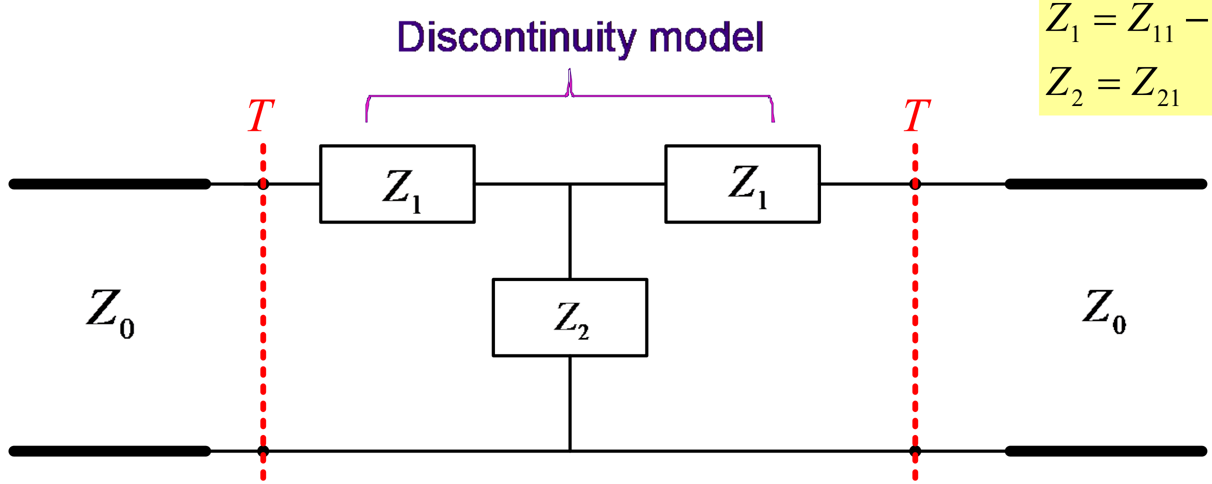
Waveguide post



Microstrip gap

We want to find Z_1 and Z_2 to model the discontinuity.

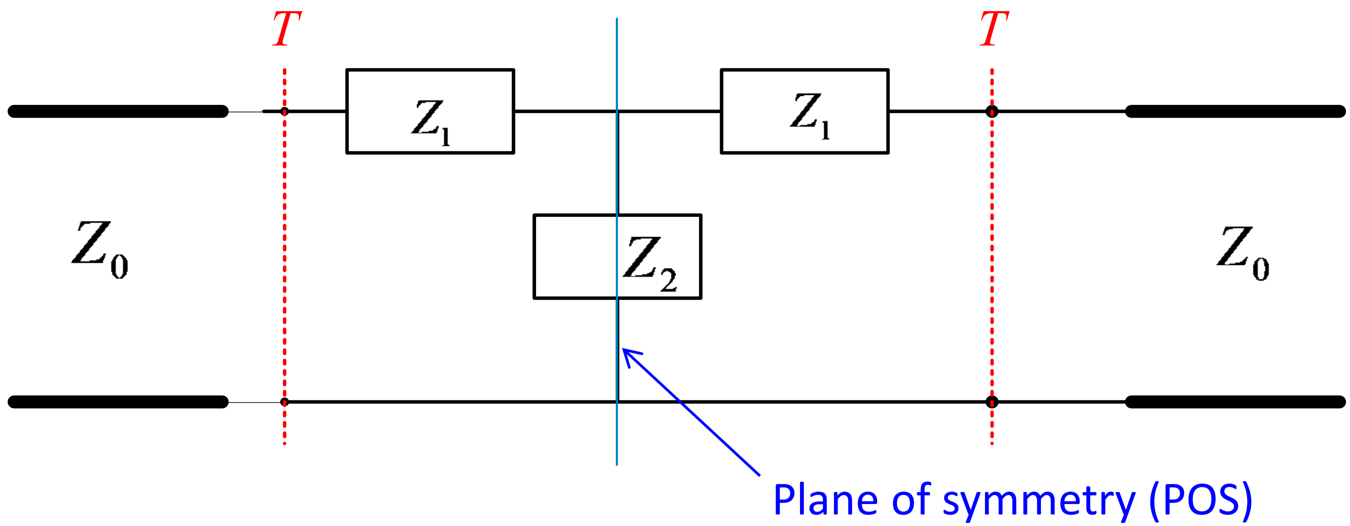
$$Z_1 = Z_{11} - Z_{21}$$
$$Z_2 = Z_{21}$$



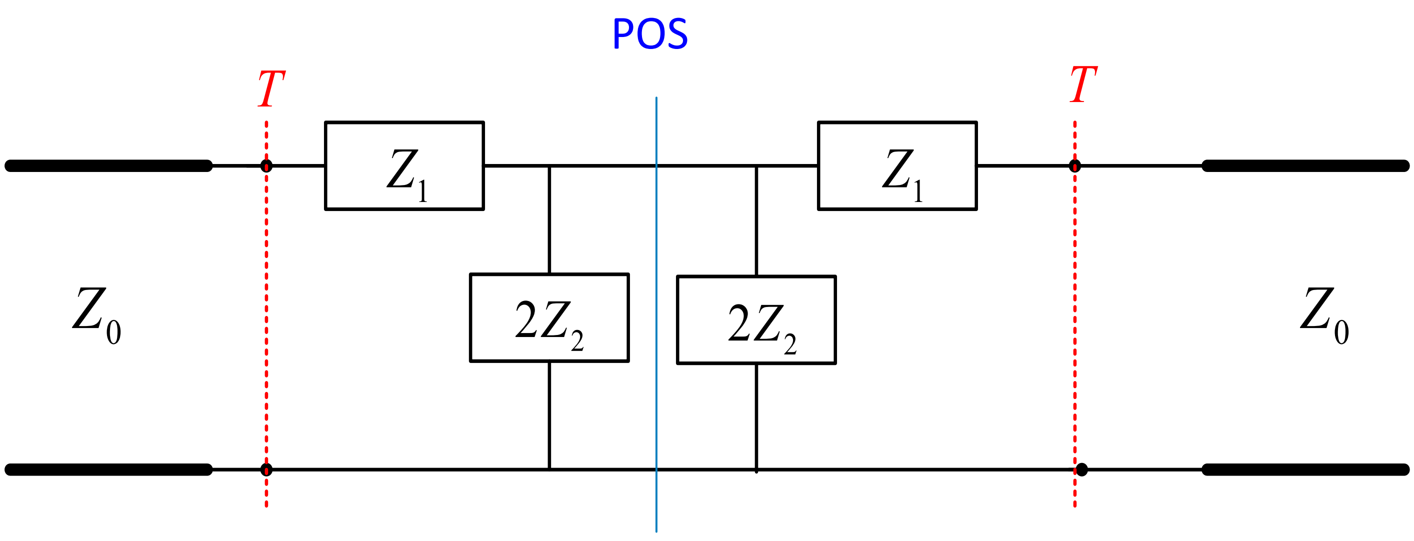
TEN

Note:
We could also use a pi network if we wish.

Z-Parameter Extraction (cont.)

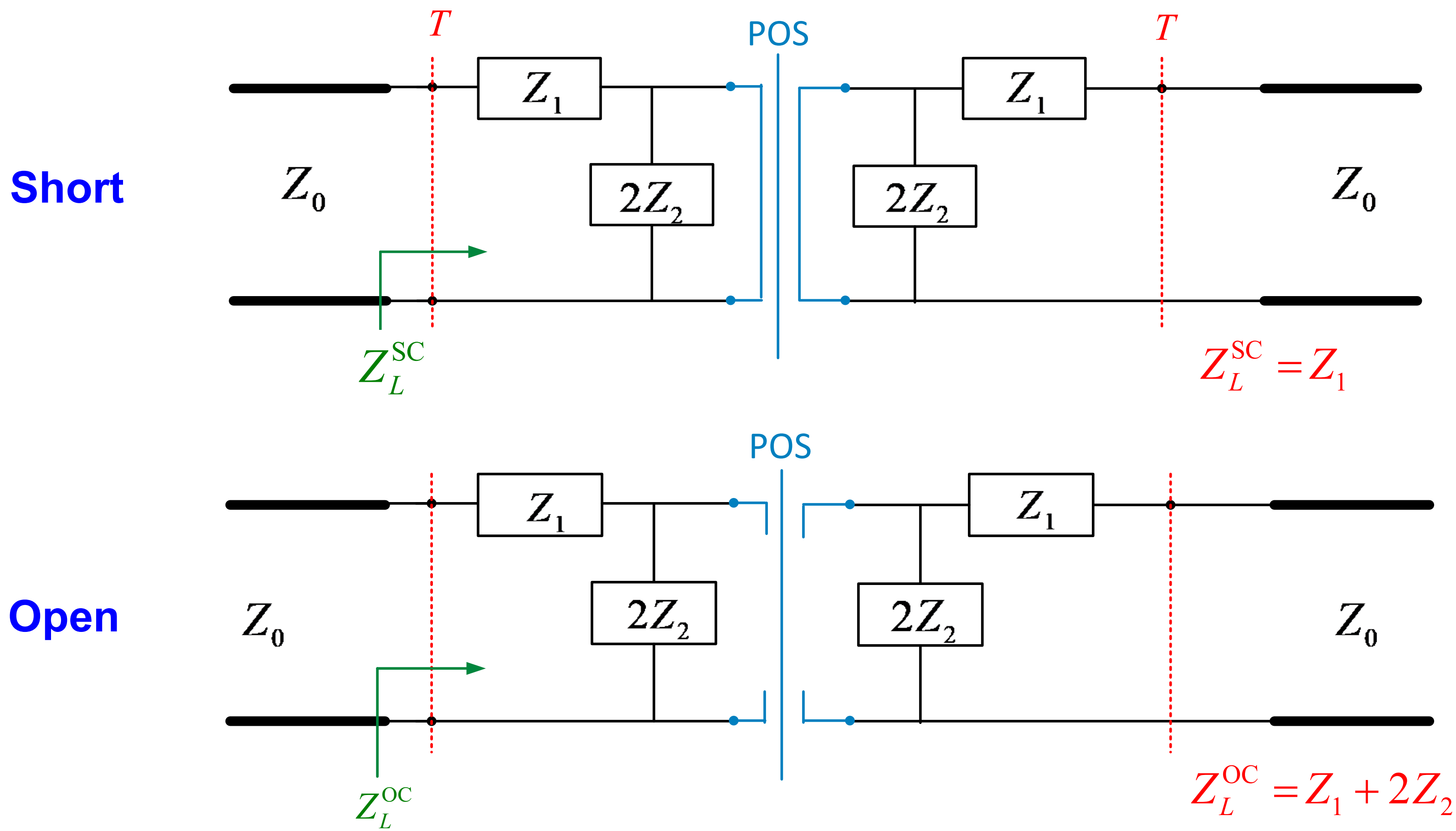


The Z_2 element is split in two:



Z-Parameter Extraction (cont.)

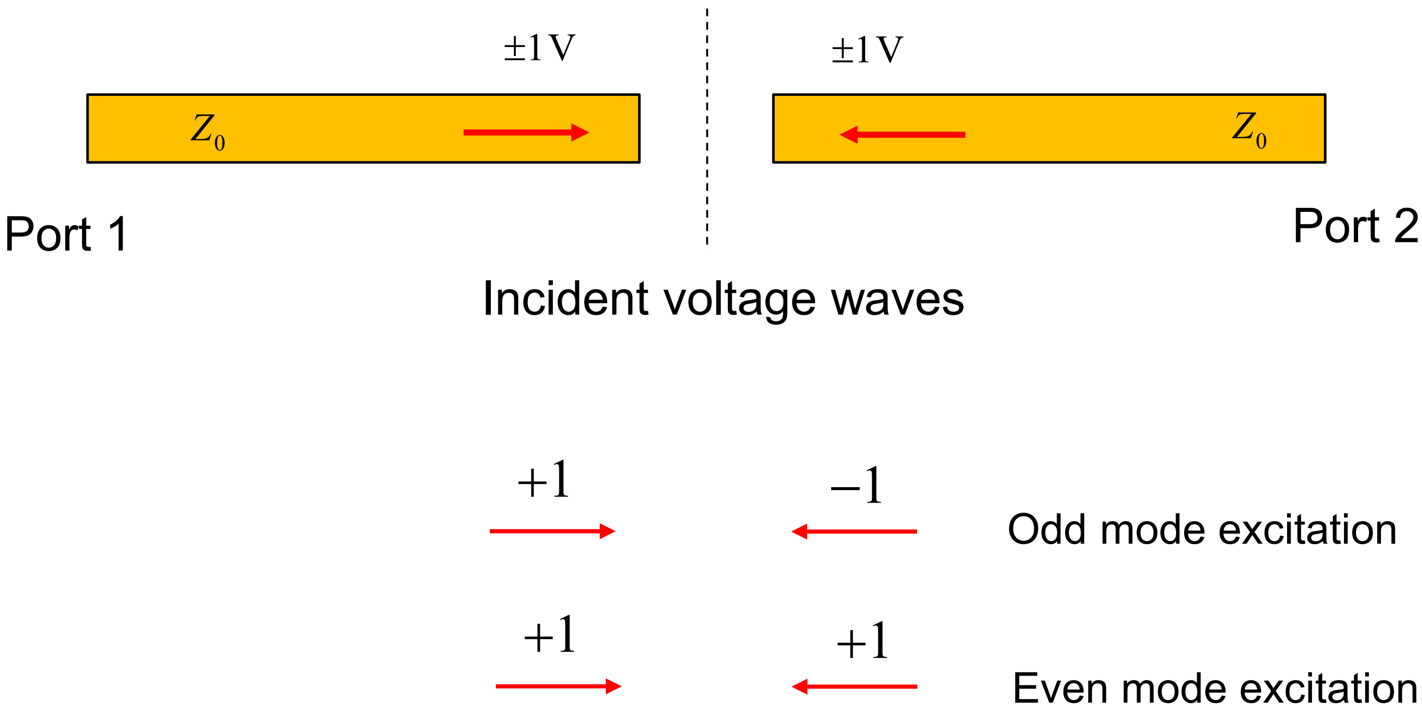
Assume that we place a short or an open along the plane of symmetry.



$$Z_1 = Z_L^{SC} \quad , \quad Z_2 = \frac{1}{2}\left(Z_L^{OC} - Z_L^{SC}\right)$$

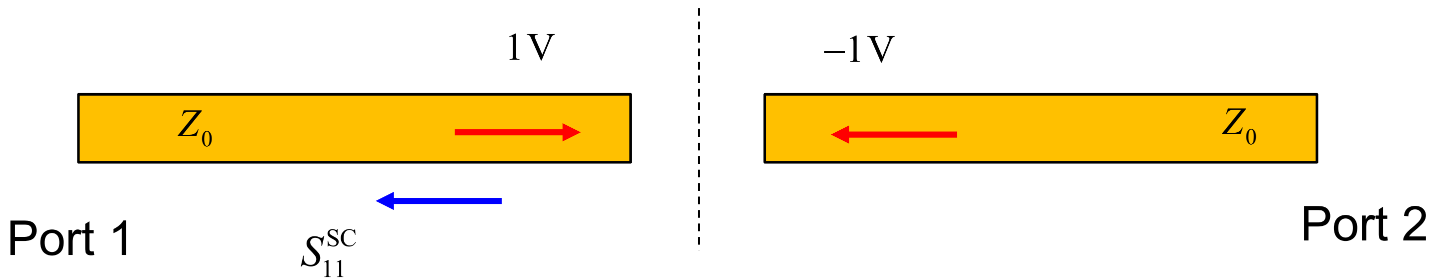
Z-Parameter Extraction (cont.)

The short or open can be realized by using odd-mode or even-mode excitation.



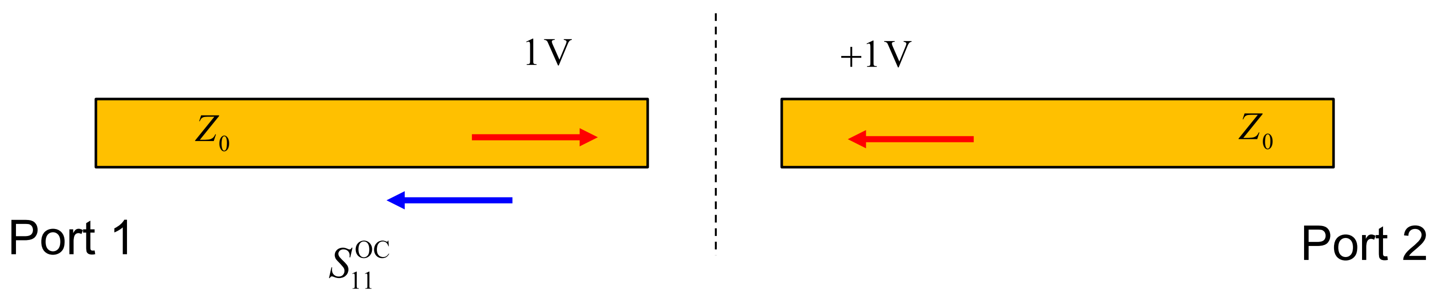
Even/odd-mode analysis is very useful in analyzing devices (e.g., using HFSS).

Z-Parameter Extraction (cont.)



Odd mode voltage waves

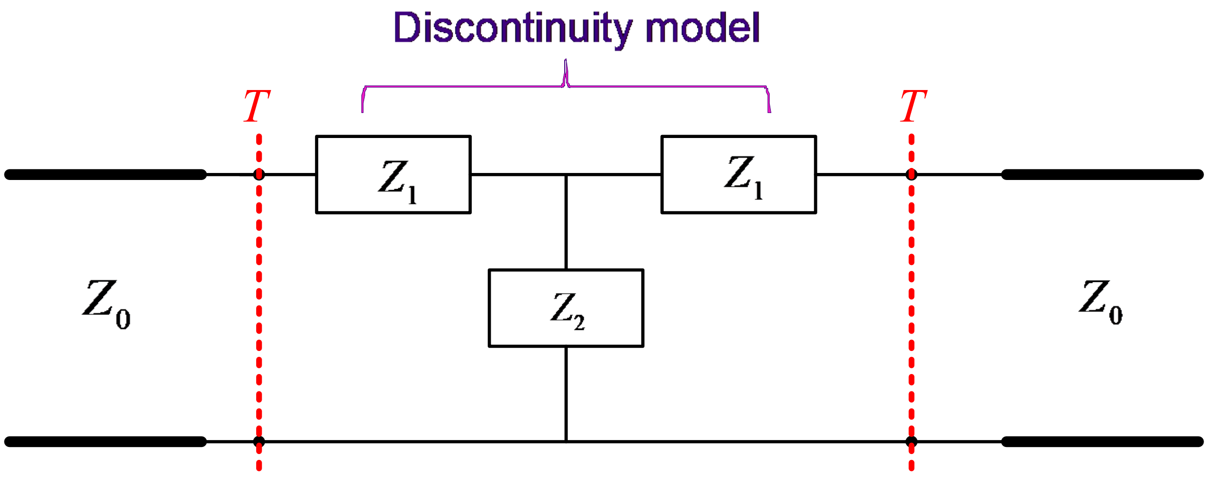
$$Z_L^{SC} = Z_0 \left(\frac{1 + S_{11}^{SC}}{1 - S_{11}^{SC}} \right)$$



Even mode voltage waves

$$Z_L^{OC} = Z_0 \left(\frac{1 + S_{11}^{OC}}{1 - S_{11}^{OC}} \right)$$

Z-Parameter Extraction (cont.)



Hence we have:

$$Z_1 = Z_0 \left(\frac{1 + S_{11}^{SC}}{1 - S_{11}^{SC}} \right)$$

$$Z_2 = \frac{1}{2} \left(Z_0 \left(\frac{1 + S_{11}^{OC}}{1 - S_{11}^{OC}} \right) - Z_0 \left(\frac{1 + S_{11}^{SC}}{1 - S_{11}^{SC}} \right) \right)$$

De-embeding of a Line Length

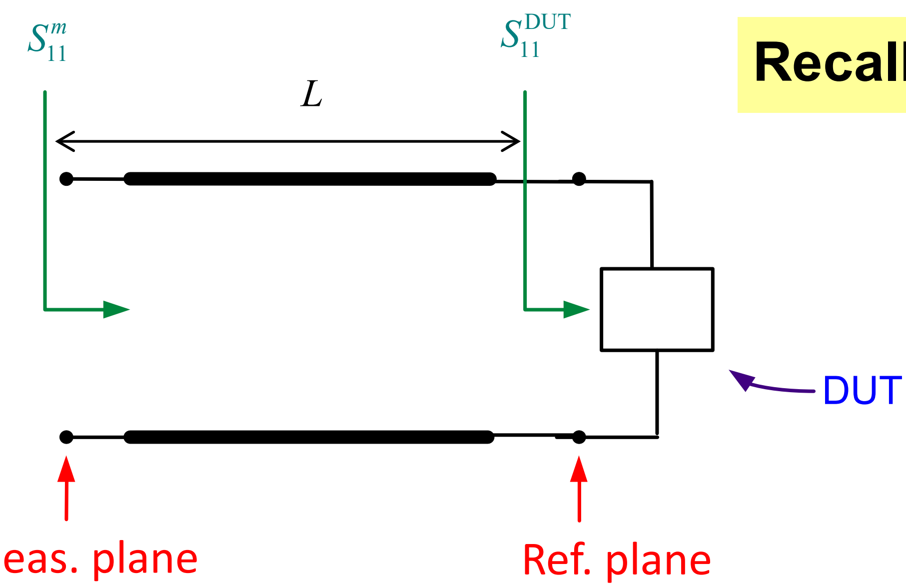
We wish the know the reflection coefficient of a 1-port device under test (DUT), but the DUT is not assessable directly – it has an extra length of transmission line connected to it (whose length may not be known).

Recall : $S'_{ij} = S_{ij}\, e^{-\gamma_i l_i} e^{-\gamma_j l_j}$

$$l_i = l_j = L$$

$$\gamma_i = \gamma_j = \gamma = j\beta$$

$$S_{11}^{\text{MEAS}} = S_{11}^{\text{DUT}} e^{-j2\beta L}$$



Replace DUT with short circuit $\left(S_{11}^{\text{DUT}} \to -1\right) \;\Rightarrow\; S_{11}^{\text{MEAS, SC}} = -e^{-j2\beta L} = -1/e^{+j2\beta L}$

$$S_{11}^{\text{DUT}} = S_{11}^{\text{MEAS,DUT}} e^{+j2\beta L}$$

$$S_{11}^{\text{DUT}} = S_{11}^{\text{MEAS,DUT}} \left(\frac{-1}{S_{11}^{\text{MEAS,SC}}} \right)$$